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DEVELOPMENT AND ADAPTATION OF A CONTROL SYSTEM FOR OPTIMIZATION OF SINGLE AND MULTIPLE OPERATION MACHINING

John S. Ramberg

JUNE 1974

U.S. ARMY ARMAMENT COMMAND

FINAL REPORT

PREPARED BY

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Iowa City, Iowa

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A system for determining optimal machining conditions based on actual production machining data is developed. This system is applicable to analysis and control of single-operation as well as multiple-operation (numerically-controlled) machining. The system incorporates a computer program which provides an evolutionary operation analysis and response surface, regression analysis of two responses, cost per piece and production rate. The output of this program provides production personnel with the information necessary for determining the optimal machining conditions for either minimum cost or maximum production.

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FOREWORD

This report was prepared by John S. Ramberg, INTERTECH Corporation, Iowa City, Iowa, in compliance with Contract No. DAAF03-73-C-0110 under the direction of the Research Directorate, GEN Thomas J. Rodman Laboratory, with R. A. Kirschbaum as Project Engineer.

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1. Introduction

Nearly every machining operation has a potential for improvement in productivity. This potential arises from the fact that the optimum machining conditions vary with the job, the machine tool, the cutting tool, and the operator.

Machining conditions for a particular job are often selected by Taylor's tool life equation, through the use of handbooks such as the Machining Data Handbook [14], or on the basis of the engineer's or operator's experience. These methods in conjunction with trial runs allow the determination of machining conditions which apparently produce satisfactory results. These machining conditions, however, are often "ball park" estimates of the optimal conditions. They are in a sense similar to the estimates of the optimal operating conditions for a chemical facility obtained by pilot plant operations. A process of "tuning" still remains to be done. However, the production personnel may leave the process "untuned" in order to concentrate their efforts on more pressing problems.

The objective of this study is to develop and to implement a system for optimizing machining conditions for single-operation and multiple-operation (numerically controlled) machine tools. The measures of productivity considered are:

1. Production cost per piece, and

2. Production rate.

This system is designed to use data collected by production personnel and to provide feedback so that the machining parameters can be adjusted accordingly. This system is based on the concept that the machining process not only generates the configuration of a part, but also generates the necessary metal-cutting information on "how to machine the part." A primary consideration in the development of this system is that the process under study should not initially be drastically changed or upset. Thus changes in operating conditions should be minor rather than major. This is accomplished through a set of rules for normal operation, so that, without serious danger of loss through the manufacture of unsatisfactory parts, an evolutionary influence is at work which steadily and automatically moves the process toward its optimal operating conditions.

This planned program of perturbations of the process variables of a machining process differs from programs of planned statistical experimentation in the following two major ways [9]:

1. The program is conducted on the machining process during actual production of a product which is expected to be shipped to the customer. In a planned experiment, the testing is usually conducted in a laboratory or pilot plant during product development. Often a scaled-down version of the final product line is involved. Since actual production is being carried out, the amplitude of perturbations introduced during the program is generally small, and sometimes effects may only be determined statistically. In a standard experimental program, the amplitude of perturbations are often maximized to determine the effects resulting more expediently.

2. The program is frequently conducted over an extended time period rather than on a one-time basis as in the case of most standard experimental programs.

Certain process characteristics are favorable to this evolutionary manner of operation, while others are unfavorable. Table 1.1 gives a list of some of these characteristics. It is particularly important to note that low volume, non-repeating job shop orders are not suitable candidates for this type of optimization. These jobs are usually completed before sufficient information is gathered to suggest optimum operating conditions.

The optimization system includes computer programs which analyze the data. The computer output is then technically evaluated by a committee. The major task of this committee is to discuss the implications of current results and to suggest potential changes. This committee should be composed of production personnel, such as the foreman and an operator, as well as staff personnel, such as an industrial engineer and a tool engineer. This committee should meet on a regular basis to review the current operations and to suggest future studies.

The technical exchange which occurs in these meetings can be more important than the information provided by the computer programs. For example, the programs can suggest new speeds and feeds at which to operate and can be used to compare different tool materials and/or different types of tool inserts. However, they can not suggest a new tool material. These types of suggestions must come from personnel familiar with the particular problem. The programs, however, help to motivate these discussions, and the improvements are accomplished through the information exchange which takes place at these meetings. The programs can also be used to evaluate and to document the performance of different cutting tools. This documentation could serve as a justification to procure proven tools of particular brands at possibly higher costs for similar future applications.

Table 1.1

Process Characteristics Which are Favorable

or Unfavorable to the Use of EVOP[9]

Characteristics Which Are Favorable	Characteristics Which Are Unfavorable
1. The process involves high volume production over a reasonably extensive time period.	1. The process is a job shop with few or no repeats of units with identical specifications.
2. The potential benefits of process improvements are large (the process is an important one and is not already operating at optimum conditions).	2. The cost for process improvement exceeds the potential benefits.
3. The process variables can be perturbed readily.	3. The process variables cannot be perturbed readily.
4. The process stabilizes rapidly after a process change.	4. The process requires a long time to stabilize after a process change.
5. The process response can be obtained rapidly.	5. The process response is not obtained rapidly (for example, if the response variable is time until failure on a life test).

Two computer programs are given in this report for optimizing machining parameters, the Performance Index Method (PIM) program and the Machining Optimization (MACHOP) program.

The PIM program, referred to as the "on-hand" program in the contract, was available from AWC[1] as a computer listing. It was designed for optimizing machining conditions of single-operation machine tools. During the initial phase of this project, the PIM program was modified, debugged, and tested on simulated data. During this same period, production data was collected at the Rock Island Arsenal (RIA) Operations Division shops. Section 2 of this report contains a discussion of the problems encountered with the PIM program and the recommendations concerning its use.[2]

Because of the difficulty in collecting data for the PIM program and in using the program with shop data, the MACHOP program was developed. The latter program can be used to optimize single-operation machine tools as well as multiple operation (numerically controlled) machine tools.

The MACHOP approach is described in Section 3. Section 4 describes the use of MACHOP, including the data handling system. Section 5 contains the MACHOP analysis of the data collected at the RIA Operations Division shops.

Appendix A contains a sample output of a regression program which was used to verify the regression modules of the PIM and MACHOP optimization programs. Appendix B contains a simulation program listing and sample output. This program was developed for preliminary analysis of the logic in the PIM and the MACHOP programs. Appendix C contains the data collection forms for the MACHOP program. An analysis of the PIM design module is given in Appendix D. Appendix E contains sample output from the Carboloy Systems Computerized Machinability Program. A program listing for the MACHOP program is given in Appendix F. Program documentation necessary for the implementation and maintenance of the MACHOP program is included as Appendix G.

2. The Performance Index Method (PIM) Program

The first phase of this contract concerned the adaptation of the "on-hand" program (herein called the PIM program) for use with single-operation machine tools. This phase of the contract required approximately 3 months.

During this period, production operations in the Rock Island Arsenal (RIA) Operations Division shops were surveyed and data collection schemes were determined. Simultaneously the PIM program was converted from a

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[1] U.S.Army Weapons Command, now U.S.Army Armament Command.

[2] Section 2 can be bypassed without loss of continuity if the MACHOP program is of primary interest.

program listing to punch cards. The program logic was checked and corrected, and the program was tested on simulated data. The results of this testing indicated some additional programming errors. Following the correction of these errors, the program performed satisfactorily on the simulated data. Details are given in Sections 2.1 and 2.2.

Major problems were encountered in the collection and analysis of production data with the PIM program. A discussion of these problems is given in Section 2.4.

2.1 Recommendations on the Use of the PIM Program

The problems which may be encountered in using the PIM program restrict its applicability. On the basis of the experience obtained in using the PIM program on RIA data, the following recommendations are made:

1. The PIM program should be used only for those machining processes or operations where the production personnel are readily able to find nine feed-speed combinations (three levels of feed for each of three levels of speed), which can be run without disturbing the production process or risking the production of scrap parts.

2. The validity of the performance index prediction outside of the region where data has been taken is highly questionable. Hence the range of prediction, which is specified in the program by the usable speeds and feeds, should be restricted. In particular the usable feeds (speeds) should be limited to <u>one feed (speed) level above and below</u> the feeds (speeds) at which data are to be collected.

3. The data collection forms developed for the <u>MACHOP</u> program should be used for collection of data for the PIM program.

4. The PIM program can be used for multiple-operation tools (numerically controlled), replacing the speed and feed variables by increments of the speed and feed overrides, respectively.

2.2 Program Logic Check

The PIM program was available as a program listing. This was converted to punch cards and verified.

Although the PIM program had been previously "debugged," a few errors were noted. A list of the changes made in the program follows:

1. Definition of Performance Index (PI)

The PI was defined in the final Report DAAF01-70-C-106a [10] as:

$$PI = Q \cdot Pr + (1 - Q)/Cu.$$

In the computer program (subroutine PERIND) the following definition was used:

$$PI = (1 - Q) \cdot Pr + Q/Cu.$$

This was corrected to agree with the report.

2. Programming Errors in the PICK Subroutine

Following the determination of the optimum feed and speed based on a given set of experimental observations, the program selects the next set of feeds and speeds by one of two methods depending on whether the previous optimal point was on a boundary. If the previous optimal point was not on a boundary, Ham [10] indicates that nine points are to be picked around the previous optimal point, subject to the maximum feed, maximum speed, and maximum horsepower constraints and tests made for uniqueness. See Appendix D for an analysis of the design strategy.

The program (PICK subroutine), however, incorrectly selected at most eight points, one of which was the first point in the previously analyzed set. The other seven points (2-8) are shown in Figure 2.1.

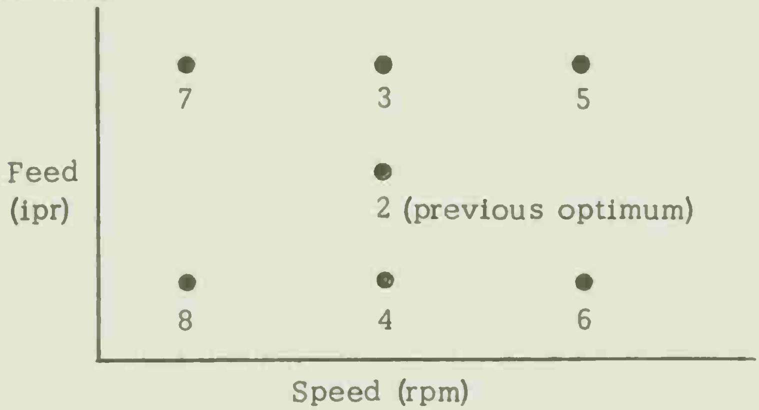

Figure 2.1 Points Selected by Design Module

To be consistent with the report and to achieve a reasonable design, line #15 of the program was changed to NPT=0 and line #25 was changed to IF(J.EQ.1) GO TO 75.

3. Format Statements

Some format statements in the program were changed to allow costs of over $10 per piece to be printed out.

2.3 Program Testing with Simulated Data

Prior to obtaining plant data, a simulation model, which is discussed below, was constructed for testing the PIM program. Some of the logic errors reported in Section 2.1 were first noted when the data from these simulations were analyzed by the PIM program.

2.3.1 The Simulation Model

The simulation model was based on the turning operation on the Monarch lathe (RIA, ID #30303) for a recoil cylinder (part #10895646). This model was constructed for the preliminary evaluation of the PIM program. This simulation is different from that discussed by Ham [10]. He used Taylor's tool life equation to determine the tool life and thus the cost. Then a random error term was introduced into the cost function. In the simulation model given here, individual tool life data are generated.[1] On the basis of these tool lives, the number of pieces produced and the number of edges used during one shift of operation are determined. Thus, the data are in the same format as the production data.

The simulation model was developed according to the following assumptions:

1. The equation used for determining the tool life is

$$VT^{\alpha}F^{\beta} = C,$$

where α, β, and C are constants,

$$V = \frac{\pi DN}{12},$$

D = Diameter of work piece in inches,

N = spindle speed in rpm,

---

[1] The tool life model does not include the possibility of tool breakage and the accompanying loss of unused edges.

F = feed in ipr, and

T = tool life in minutes.

If one takes logarithms, the above tool life equation can be written as

$$\ln T = \frac{1}{\alpha}[\ln C - \beta \ln F - \ln V].$$

A random error term, ϵ, is added to the above equation to introduce variability into the tool life. The error term, ϵ, is assumed to have a normal distribution with mean zero and standard deviation of

$$\frac{1}{\alpha}[\ln C - \beta \ln F - \ln V] \cdot ERR,$$

where ERR is the percentage error appropriate for the process.

2. An eight hour day, allowing for the operator's personal time, is assumed to consist of 420 minutes of production time.

3. If at the end of a shift, a part is over 75% finished, it is assumed to be completed.

A flow chart based on the above assumptions is given in Figure 2.2. The computer program, written in FORTRAN IV and a sample output are given in Appendix B.

2.3.2 Analysis of Simulation Data

The center of the initial set of points selected was $V = 220$ rpm and $F = 0.0187$ ipr. Although the PIM program will operate with as few as six design points, Ham's [10] recommendation of nine points in a geometric pattern of a 3^2 factorial design was followed. A large range of feeds and speeds were available on the Monarch lathe. However, the usable speed range was limited to 95 rpm - 330 rpm and the usable feed range was limited to 0.007 ipr - 0.0337 ipr.

The data generated by the simulation program for the first experiment are given in Table 2.1.

Based on these data, the on-hand program selected the optimal speed and feed as $V = 220$ rpm and $F = 0.0337$ ipr. Note that this is on the usable feed boundary. Hence, feed is no longer adjustable. The points suggested for the next experiment and the simulated production data for these points are given in Table 2.2.

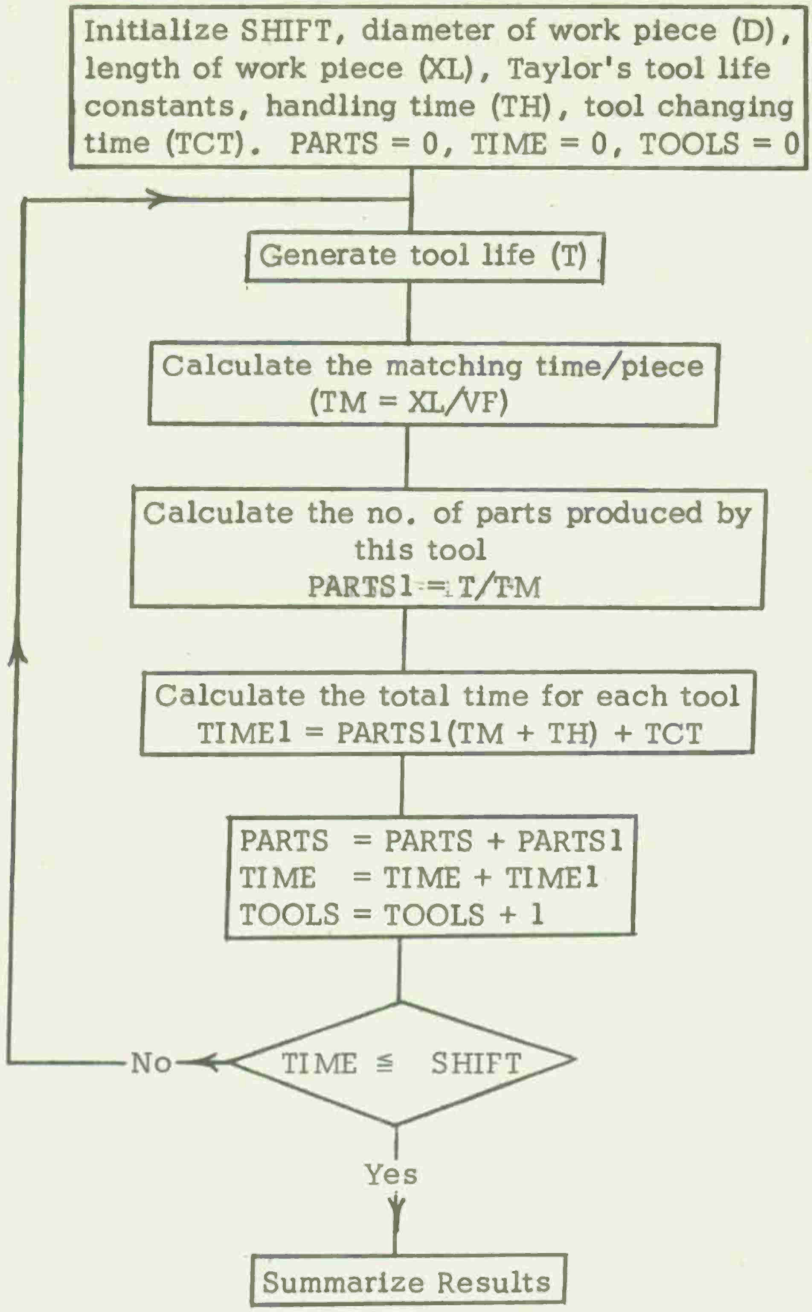

Figure 2.2 Simulation Flow Chart

Table 2.1 First Data Set

Speed	Feed	No. of parts	Time	No. of edges
192	0.0168	14.0	420.0	8.0
192	0.0187	14.0	420.0	11.0
192	0.0210	15.0	420.0	14.0
220	0.0168	14.0	420.0	16.0
220	0.0187	15.0	420.0	20.0
220	0.0210	16.0	420.0	21.0
255	0.0168	14.0	420.0	36.0
255	0.0187	15.0	420.0	32.0
255	0.0210	16.0	420.0	31.0

Table 2.2 Second Data Set

Speed	Feed	No. of parts	Time	No. of edges
166	0.0337	17.0	420.0	9.0
220	0.0337	19.0	420.0	17.0
290	0.0337	19.0	420.0	45.0
330	0.0337	18.0	420.0	64.0

Based on these data, the PIM program selected the optimal speed and feed as 220 rpm and 0.0337 ipr. Since the two previous optimal points were not identical, the PIM program selected a new set of five points on the feed boundary. The feed and speed settings and the simulated data for these 5 points are given in Table 2.3.

The point 220 rpm, 0.0337 ipr was again chosen as the optimal point. The analysis was terminated since the same point was chosen on two consecutive runs.

Table 2.3 Third Data Set

Speed	Feed	No. of parts	Time	No. of edges
126	0.0337	16	420.0	6.0
166	0.0337	18	420.0	2.0
220	0.0337	18	420.0	22.0
290	0.0337	19	420.0	46.0
330	0.0337	18	420.0	63.0

A graphical presentation of these results is given in Figures 2.3 and 2.4.

The PIM program required 18 observations to obtain the optimal feed and speed. Table 2.4 gives the cost per piece in dollars for some of the usable feeds and speeds for the case where ERR is 0.

Table 2.4 Cost/Piece ($) as Given by Taylor's Equation

Feed (ipr) \ Speed (rpm)	145	166	192	220	255	290	330
0.0153	11.76	10.89	10.24	10.47	10.05	10.44	10.95
0.0168	10.78	10.05	10.24	9.72	9.38	9.74	10.22
0.0187	10.78	10.08	9.51	9.07	9.38	9.74	10.22
0.0210	9.95	9.36	8.88	9.10	8.79	9.14	9.58
0.0240	9.24	8.74	8.35	8.53	8.30	8.60	9.02
0.0337	8.11	7.71	7.42	7.58	7.41	7.67	8.47

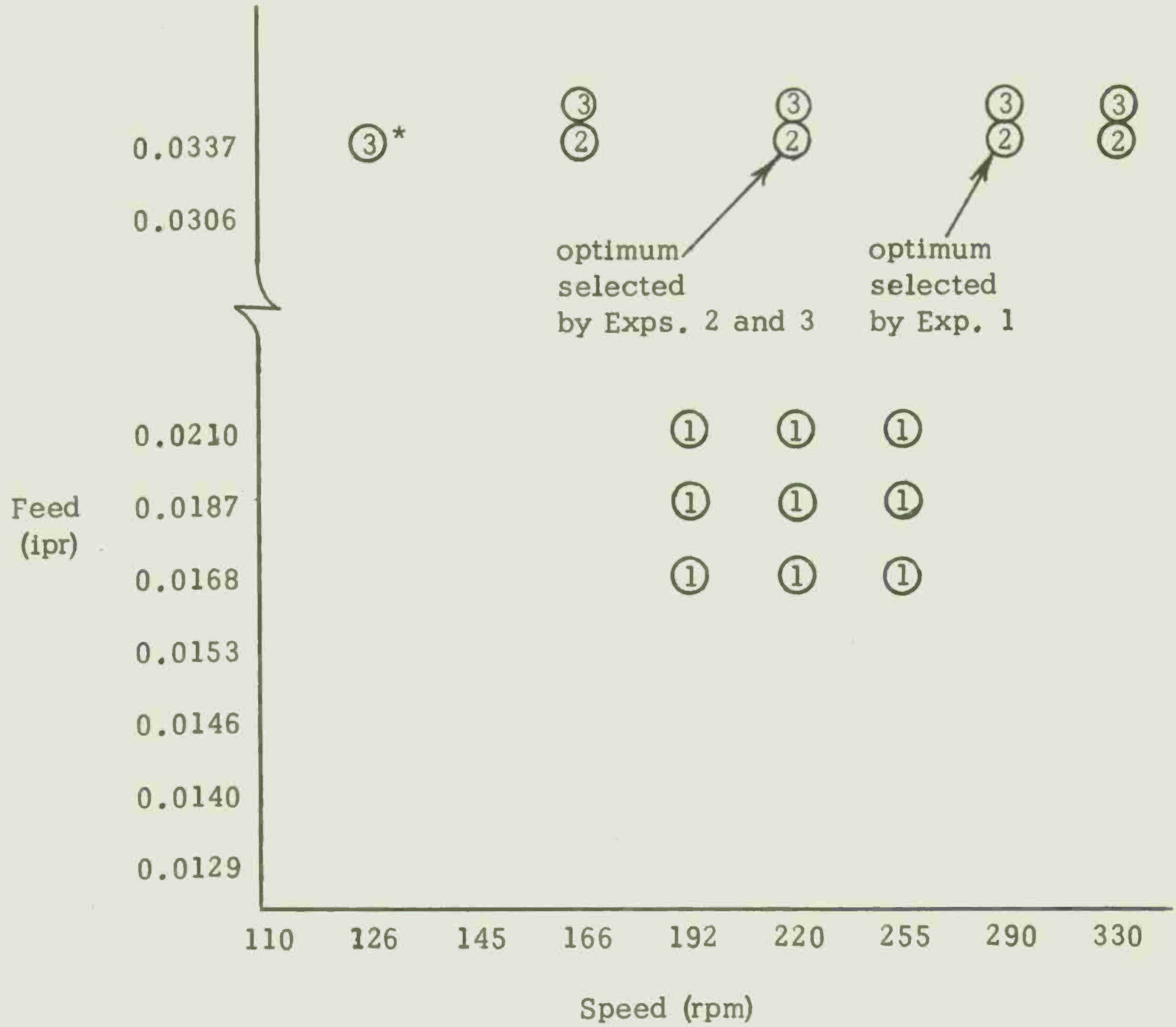

Figure 2.3 Design Points for the PIM Method

*the circled numbers indicate the experiment number, i.e., i indicates that this point is in the i^{th} experiment.

Feed (ipr)	126	166	192	220	255	290	330
		7.05^{3}		7.51^{3}		7.65^{3}	8.47^{3}
0.0337	8.03^{3} *	7.63^{2}		7.01^{2}		7.63^{2}	8.49^{2}
0.0210			8.97^{1}	8.43^{1}	8.69^{1}		
0.0187			9.33^{1}	8.96^{1}	9.30^{1}		
0.0168			9.24^{1}	9.48^{1}	10.08^{1}		

Speed (rpm)

Figure 2.4 Cost/Piece Estimates ($) at Observed Feeds and Speeds

*The superscripts refer to the experiment number.

2.4 Program Testing with Rock Island Arsenal (RIA) Data

This phase of the study required a major portion of time and dollar expenditures of the research project. All previous experimentation using the PIM program was based on simulated data and/or a very limited amount of laboratory experimental data.

A turning operation on a recoil cylinder using the Monarch lathe was selected for the first study. Other information concerning this operation is given in the job description in Table 2.5.

Table 2.5 Job Description for First Study

Operation: - Turning

Part: - Variable recoil cylinder

Material: - Steel tube 4140.

Dimensions: 47.5" long, 8.5" dia., depth of cut 1/8"

Job order #: 0016011

Part #: 10895646

Cutting tool: - Titanum coated carbide insert, multi-edged

Tool cost/edge: - $.42

Machine tool specifications: Monarch stepped lathe.
50 HP. RIA ID #30303

Available speeds (in rpm): 84, 95, 110, 126, 145, 166, 192, 220, 255, 290, 330, 380, 435

Available feeds (in ipr): .0032, .0035, .0037, .0038, .0042, .0047, .0013, .0060, .0065, .0070, .0073, .0076, .0084, .0093, .0105, .0120, .0129, .0140, .0146, .0153, .0168, .0187, .0210, .0240, .0259, .0293, .0306, .0337, .0374, .0421, .0451, .0518, .0561, .0585, .0612, .0673, .0748, .0841, .0962, .1036, .1122, .1171, .1224, .1346, .1496, .1683.

Labor and overhead rate: - $18/hr.

A 3^2 factorial experiment[1] was conducted with V = 220 rpm and F = 0.0187 ipr as a center point. Each of the nine feed-speed combinations was used for one shift of operation. The same operator was used for all of the points. The data in Table 2.6 were recorded by the machine operator.

Based on the above production data, the cost per piece in dollars is calculated in each case and is given in the last column of Table 2.6. In this case the performance index is taken as 1/Cu.[2] The PIM program fits a regression equation of the form $PI = b_0 + b_1V + b_2F + b_3V^2 + b_4F^2 + b_5V \cdot F$ to the data. (See Ham [10] for a more complete discussion.) The performance index is evaluated at all usable feed-speed combinations.

Table 2.6 Data Summary for Experiment 1
Results for Recoil Cylinder - First Study

Speed (rpm) V	Feed(ipr) F	No. of parts	Production time	No. of tool edges	Cu $/piece
192	0.0168	14	434	17	9.51
192	0.0187	18	410	18	7.28
192	0.0210	14	377	18	8.63
220	0.0168	13	396	23	9.90
220	0.0187	15	393	15	8.28
220	0.0210	20	440	44	7.52
255	0.0168	10	217	17	7.22
255	0.0187	11	267	29	8.39
255	0.0210	14	357	31	8.58

The optimal feed-speed combination is selected as the point which maximizes the predicted performance index PI and thus minimizes the predicted cost, Cu.

---

[1] An experiment conducted at 3 levels on each of 2 factors, resulting in a total of 9 experimental points.

[2] The reciprocal of Cu, the cost per piece, in $/piece.

The feed-speed combination selected as optimal was V = 95 rpm and F = 0.0187 ipr. At this combination the performance index prediction is PI = 0.212 and hence the cost estimate is Cu = \$4.72/piece. However, a few calculations illustrate that the predicted cost cannot be achieved at this feed and speed.

The machining time per piece is 47.5/(95 x .0240) = 20.8 min/piece. Allowing nine min/piece handling and no time for tool change we arrive at a total time of 29.8 min/piece. Using the labor plus overhead rate of \$18/hr and neglecting the tool costs, we obtain a conservative estimate of cost per piece of \$9.00/piece. This is nearly double the cost predicted by the PIM program. It is also higher than the cost per piece for many of the original nine feed-speed combinations.

The cost estimates obtained by the PIM program for a number of feed-speed combinations are given in Table 2.7. (These are not printed by the PIM program but are easily obtained.)

The regression calculations in the PIM program were also verified by analyzing the data on a separate regression program. (See Appendix A.) No substantial differences were noted. The prediction equation explained 37.3% of the variability in the data.

Table 2.7 Cost/Piece Predictions (\$) Using the PIM Program

Feed (ipr) \ Speed (rpm)	95	145	166	192	220	255	290
0.0153		14.59	14.04	12.75	10.97	8.75	6.88
0.0168	8.67	9.81	9.90	9.66	9.01	7.87	6.61
0.0187	6.24	7.46	7.84	8.10	8.09	7.65	6.85
0.0210	5.10	6.49	7.08	7.76	8.32	8.59	8.19
0.0240	4.72[1]	6.69	7.82	9.53	11.71	14.98	16.62

[1] Indicates the optimal point.

The major reason for this failure of the PIM program is the large amount of variability present in the data. Due to this high variability in the shop data, the prediction equation used in the PIM program was valid only over a small region of feed-speed combinations where the data were collected.

One method of reducing the variability of the prediction equation is to take data for at least two shifts at each feed-speed combination.[1] However, this would require data from eighteen shifts of operation. This does not appear to be a viable alternative because of the excessive length of time required to collect the data prior to feedback.

It should also be noted that the specification of constraints such as the horsepower constraint did not seem to be of any value. This is probably attributable to the fact that the mathematical expressions for the constraints are only approximations. Determination of feasible operating feed-speed combinations would be better left to shop personnel. These points can be determined on the basis of experience and trial runs.

Another problem was encountered in collecting shop data for the PIM program. The program requires a minimum of six feed-speed combinations. (Actually nine combinations are recommended in the users instructions.) On the operations observed in the RIA shop it was difficult to select three feeds and three speeds (yielding nine feed-speed combinations) without taking a high risk of producing scrap parts at one of these combinations.

Since the PIM program functioned satisfactorily with the simulated data, some commentary seems to be in order concerning the differences between the simulated data and the production data.

Whereas the simulation model assumed that the handling time and the total production time were constant, namely 15 min/part and 420 min/day, respectively, the quantities were highly variable in the actual production situation. The handling time varied from 9 min/part to 15.8 min/part, while the production time varied from 217 min/day to 440 min/day. The variation in the handling time leads to much higher variability in the estimates of the performance index. The production time variability illustrates the need for recording down time, rather than using the eight hour work shift as a time base. Another major difference between the simulation model and the real production situation is that the tool lives for the simulation model were determined by the tool life equation with a 20% random error term added. In the shop the variability was even higher due to tool breakage. Since "triangular throw away" inserts were being used, breakage of the tool could result in a loss of one to six edges at one time.

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[1] The complete experiment should be performed using the same operator, if possible, so that an additional source of variability is not introduced. Data from long runs by multiple operators may be averaged.

3. The Machine Optimization (MACHOP) Program

The problems encountered in the collection of data and in the application of the PIM program indicate the importance of the following objectives for development of a usable optimization program:

1. A limited number of feeds and speeds should be attempted and analyzed initially in order to provide early feedback and to minimize disruption to the shop operation.

2. Since changes in feeds and speeds must be gradual, it is initially sufficient for the optimization program to determine the direction of the optimal operating conditions rather than selecting a particular feed-speed combination as optimal. This procedure will greatly reduce the chances of incorrectly determining the optimum feed-speed combination. This is particularly important because of the variability in shop data.

3. At most two variables should be varied simultaneously to facilitate the usage and understanding by production personnel.

The MACHOP program is designed to accomplish the above objectives in addition to those specified in the contract. No constraints other than the definitions of the speed and feed environment are considered in this process. Although certain constraints were directly incorporated into the PIM program, they were not incorporated into the MACHOP package. The data collected in this project indicates that the mathematical expressions for these constraints (i.e., the horsepower or the surface finish) were only crude approximations. Hence it seemed better to rely on the shop personnel's experience than to eliminate a particular operating point because of a constraint equation. In addition, these constraints are not as critical to the MACHOP program as they were to the PIM program, since the MACHOP program moves in small steps toward the optimum operating conditions.

To simplify the collection of data in the shop, observations are always taken in sets of four at two adjacent feeds and two adjacent speeds. For numerically-controlled multiple-operation machine tools the feeds and speeds are controlled by feed and speed overrides. This procedure avoids the cost of preparing new NC tapes for each run.

For each feed-speed combination, the following data are collected during one shift of operation:

1. the number of parts produced,

2. the number of tool edges used for each tool type, and

3. the production time.[1]

These results are submitted to the MACHOP program.

On the basis of these data the MACHOP program calculates two performance indices:

1. the cost/piece (Cu) in dollars/piece, and
2. the production rate (Pr) in pieces/minute.

The MACHOP program then performs two types of analyses for each of the responses or performance indices:

1. an evolutionary operation analysis, and
2. a response surface, regression analysis.

The evolutionary operation analysis is based on the work of Box and Draper [3]. An automatic feedback provision for systematic optimization is given in this portion of the program. The program recommends a set of four feed-speed combinations for the next phase or cycle of operation. (This set of feed-speed combinations may be the same as the set just completed.) The evolutionary operation analysis makes no assumptions concerning the form or shape of the response surfaces. Its purpose is to evaluate the differences in the observed responses at the four feed-speed combinations as compared to the variability of the process and to suggest the direction of movement toward the optimal machining conditions.

The response surface, regression analysis uses the same data as the evolutionary operation analysis. The parameters of two regression equations are estimated, and these equations are used to predict the responses at the feed-speed combinations in the region in which data have been collected. When sufficient data are available, second order equations are fitted to the natural logarithms of the feeds and speeds. Each of these second order equations requires the estimation of six parameters, and hence, at least six different feed-speed combinations are necessary to estimate all the parameters.

When data has been collected at fewer than six feed-speed combinations, lower order equations are used. For example, for the initial set of four feed-speed combinations, first order models are fitted to the data, and used to make the predictions. In addition to the predictions, analysis of variance tables are also provided.[2] An understanding of regression analysis is not necessary for program use. Production personnel will generally be interested only in the predictions.

---

[1] Actual cutting, work piece handling and tool changing time.

[2] A complete discussion of regression and analysis of variance tables is given in references [4] and [5].

The output of these two portions of the program serves as the basis for the MACHOP committee's discussion concerning the next phase or cycle of experimentation. In general, the committee should follow the MACHOP suggestions, unless their collective experience indicates otherwise. The prediction output gives them an indication of both the unit costs and the production rates at adjacent feeds and speeds.

On the basis of this information the committee can also make decisions such as the following:

1. try a new cutting tool,

2. try a different machining process, or

3. prepare a new tape for an N/C job.

A new cutting tool might be suggested upon collaboration by the tool engineer and the operator. It might be determined that a more expensive cutting tool is warranted by a corresponding increase in production rate and/or reduction in total cost. A different machining process might be proposed in order to decrease high machining costs for particular parts. The suggestion to prepare a new tape might result from the fact that the MACHOP program suggests that an override be increased by 5%, although the upper limit has already been attained. Under these circumstances it may be economical to prepare a new tape. This situation could also occur if the program suggested increasing an override, but the operator felt that this change would have a negative effect on one or more of the machining operations. In this case a new tape could be prepared which would change the feeds and/or speeds of a particular set of operations relative to the feeds and/or speeds of the other operations. Following any of these changes, the usual data should be collected and submitted to the program in order to investigate and to document the effect of the change.

The technical aspects of the MACHOP program are discussed in the subsequent sections. Section 3.1 gives information on the performance index calculations. The details of the evolutionary operation portion of the program are given in Section 3.2, and the response surface-regression analysis portion of the program is discussed in Section 3.3.

3.1 Computation of Performance Indices

The two performance indices used in the MACHOP program are

Cu = Cost per piece ($/piece), and

Pr = Production rate (pieces/minute).

These quantities are calculated for each of the test points.

For a given test point the following data are collected:

N_p = Number of parts produced,

N_{ti} = Number of tool edges of tool i used, and[1]

T = Time period of test (in minutes).

The test will usually consist of running at a given feed and speed for one shift. Forms for collecting these data are provided in Appendix C. Note that the length of the test will usually be less than the shift time because of interruptions for other activities such as safety meetings and personal time.

The production rate computation for single-operation, multiple-operation, and/or numerically controlled processes is

$$Pr = N_p/T.$$

For a single-operation machining process the cost per piece is

$$Cu = [\,(RLO)T + (TLC)N_t\,]/N_p$$

where

RLO = Labor and overhead rate in dollars per minute, and

TLC = Tool cost in dollars per edge.

If the objective is to minimize tool cost per piece then RLO is set equal to zero. Alternatively, the overhead may be removed from the problem by setting RLO equal to the labor rate.

For a multiple-operation machining process the cost per piece is

$$Cu = [\,(RLO)T + \sum_{i=1}^{n} (TLC_i)N_{ti}\,]/N$$

where

n = Number of different tools, and

TLC_i = Cost of tool i in dollars per edge.

---

[1] N_{t1} is shortened to N_t.

3.2 Evolutionary Operation (EVOP)

Evolutionary operation (EVOP) is a method of process improvement that:

1. is readily conducted under actual processing conditions by production personnel,

2. operates despite the presence of large experimental error,

3. provides an efficient basis for scientific or technological feedback, and

4. does not assume knowledge of the functional form of the response surface or any explicit knowledge of the response function except that it is smooth.

EVOP computations and procedures for analyzing the results of the 2^2 factorial experiment are based on the work of Box and Draper [3][1]. In this analysis, the two performance indices, Cu and Pr, are examined as a function of the feed and speed of the machining operation. The effect that each of these factors exerts on the performance indices is evaluated and two (possibly identical) sets of operating conditions are suggested for future operation.

3.2.1 EVOP Calculations

A cycle is a set of four observations in a rectangular pattern at two adjacent feeds and two adjacent speeds. This set of four observations allows the determination of the effect of

1. feed,

2. speed, and

3. feed-speed interaction

on both the production rate and the cost per piece.

---

[1] Box and Draper also consider a 2^2 factorial design with an additional reference condition. This approach, if used here, would require taking data at three feed and speed levels. Experience with the machining operations at the RIA shops indicated that this was too wide a range and could lead to production of scrap. Hence, the 2^2 factorial design without reference condition was chosen.

A phase consists of repetitions of the same cycle. In other words, phase indicates which set of four points is being observed and cycle indicates the number of observations which has been taken at each feed-speed combination during this phase. Cycles are repeated within a phase until sufficient information is gathered on the effects of feed, speed and their interaction to suggest a new set of feed-speed combinations, i.e., a new phase of operation. The new phase begins when observations are taken at a new set of feed-speed combinations. The concepts of phase and cycle are important in understanding the EVOP analysis. A minimum of two cycles of observations are required in Phase 1 to estimate the variability of the data. Prior estimates of the variability can also be used as will be discussed later. The estimate of variability is necessary to determine the significance of the effects of feed and speed on the responses. Moving to a new phase constitutes the movement across the response surface. Taking another cycle means additional information is being gathered to determine the direction of movement.

The EVOP computations of Box and Draper [3] have been modified to accomodate machining data and to facilitate computerization. The computational procedure is summarized in Figure 3.1. A complete discussion of these calculations is given for phase M and cycle n.

The first step in the EVOP analysis is the calculation of the phase averages and phase ranges. These computations are the same for each of the performance indices. The performance index will be denoted by y in the following discussion. Each of the performance indices are calculated for each feed-speed combination, for which data are available, according to the equations given in Section 3.1. For cycle n the new observations at each of the four feed-speed combinations are denoted by y_{in} $(i=1,2,3,4)$. The previous cycle sum (PCS_i) at each of these four points is given by

$$PCS_i = \sum_{j=1}^{n-1} y_{ij}.$$

Thus, the previous cycle average is

$$\overline{y}'_i = PCS_i/(n-1).$$

The four differences (d_i) are calculated by subtracting the new observations from the previous cycle averages, i.e.,

$$d_i = \overline{y}'_i - y_{in}.$$

These differences are used to estimate the variability of the data. The new sums (NS_i) are computed as the sum of the previous cycle sums and the new observations

$$NS_i = PCS_i + y_{in}.$$

Finally the new averages are calculated as

$$\overline{y}_i = NS_i/n$$

for each of the four feed-speed combinations.

The new averages are the values used to determine the effects of the factors on the performance index. The new cycle sums and the new cycle averages become the previous cycle sums and previous cycle averages for the next cycle (i.e., cycle n + 1), if the current phase is continued.

For the first cycle of any phase, the previous cycle sums and the previous cycle averages are zero by definition. The new sums and new averages (NS_i and $\overline{y}_i$) are just the new observations. The range is not meaningful and hence is not calculated for this cycle. If this is the first phase, there is no measure of error with which to compare the effects of the factors. This is the reason that a minimum of two cycles in the first phase is required to produce an initial estimate of the standard deviation of the error of the response. In later phases, the estimate obtained from previous phases is used.

The effects of the factors, feed and speed, are calculated using the new averages $\overline{y}_i$. Consider the 2^2 factorial design configuration as in Figure 3.1. Each $\overline{y}_i$ is associated with a point i in Figure 3.1. Speed increases from left to right as depicted by the arrow. The effect of speed is given by

$$\text{SPEED EFFECT} = \frac{1}{2}\left((\overline{y}_2 + \overline{y}_3) - (\overline{y}_1 + \overline{y}_4)\right) = \frac{1}{2}(\overline{y}_2 + \overline{y}_3 - \overline{y}_1 - \overline{y}_4).$$

Feed increases as indicated by the labeled arrow and the effect of feed is given by

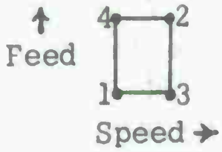
$$\text{FEED EFFECT} = \frac{1}{2}\left((\overline{y}_2 + \overline{y}_4) - (\overline{y}_1 + \overline{y}_3)\right) = \frac{1}{2}(\overline{y}_2 + \overline{y}_4 - \overline{y}_1 - \overline{y}_3).$$

The effect of the interaction of speed and feed is given by

$$\text{SPEED-FEED (INTERACTION) EFFECT} =$$

$$\frac{1}{2}\left((\overline{y}_1 + \overline{y}_2) - (\overline{y}_3 + \overline{y}_4)\right) = \frac{1}{2}(\overline{y}_1 + \overline{y}_2 - \overline{y}_3 - \overline{y}_4).$$

(2^2 Factorial)



PHASE =

CYCLE(n) =

Calculation of Averages					Calculation of Standard Deviation
Operating conditions	(1)	(2)	(3)	(4)	
(i) Previous cycle sum	PCS_1	PCS_2	PCS_3	PCS_4	
(ii) Previous cycle average	$\bar{y}_1'$	$\bar{y}_2'$	$\bar{y}_3'$	$\bar{y}_4'$	Previous average S =
(iii) New observations	y_{1n}	y_{2n}	y_{3n}	y_{4n}	New S = range $\times f_{4,n}$ =
(iv) Differences (ii) less (iii)	d_1	d_2	d_3	d_4	Range=$\underset{i}{MAX}[d_i]-\underset{i}{MIN}[d_i]$=
(v) New sums	NS_1	NS_2	NS_3	NS_4	New sum S=S'+New S =
(vi) New averages: $\bar{y}_i$	$\bar{y}_1$	$\bar{y}_2$	$\bar{y}_3$	$\bar{y}_4$	New average S = New sum S/2 =

Calculation of Effects	Calculation of 2 S.E. Limits
SPEED effect = $\frac{1}{2}(\bar{y}_2 + \bar{y}_3 - \bar{y}_1 - \bar{y}_4)$ =	
FEED effect = $\frac{1}{2}(\bar{y}_2 + \bar{y}_4 - \bar{y}_1 - \bar{y}_3)$ =	For new effects:
SPEED-FEED effect = $\frac{1}{2}(\bar{y}_1 + \bar{y}_2 - \bar{y}_3 - \bar{y}_4)$ =	$\pm \frac{2}{\sqrt{n}} S$ =

n	1	2	3	4	5	6	7	8	9	10
$f_{4,n}$	0	0.34	0.40	0.42	0.43	0.44	0.45	0.45	0.46	0.46

Figure 3.1 Evolutionary Operation

The variability of the data is measured by the standard deviation (S) of the observation errors, and the computational procedure to obtain it for phase M cycle n is described subsequently. The new S for cycle n is computed as the range multiplied by the factor $f_{4,n}$ (given in Figure 3.1) as follows:[1]

$$\text{New } S = \text{Range} * f_{4,n} \;,$$

where $\text{Range} = [\max_i(d_i) - \min_i(d_i)]$. The new sum S is then computed as

$$\text{New sum } S = (S' + S),$$

where S' is the previous sum S. The new average S ($\bar{S}$) is equal to the new sum S divided by 2:

$$\bar{S} = (\text{New Sum } S)/2.$$

As indicated, the standard deviation is a weighted average of the standard deviations of all previous cycles.

When a prior estimate of the standard deviation of the response variable is known, it can be used as a substitute for the computed standard deviation during the initial phase. Having reached the second cycle in any phase, however, the prior estimate of the standard deviation is disregarded, and the computed standard deviation is used.

For any cycle $(n > 1)$, the standard deviation is recomputed as indicated. For the first cycle of a new phase (i.e., $n = 1$), the standard deviation from the last phase is used. For $n > 1$ the standard deviation is updated as above.

The standard error (SE) is calculated as follows:

$$SE = \bar{S}/\sqrt{n},$$

where n is the cycle number, and $\bar{S}$ is the estimate of the standard deviation.

3.2.2 Direction of Movement on the Response Surface

Based on the results of the EVOP calculations, the MACHOP routine selects a set of operating conditions. This may be another cycle in the current phase (i.e., new observations at the same four feed-speed combinations) or a new phase may be initiated (i.e., observations at a different set of four feed-speed combinations). In either case, MACHOP recommends the four points (i.e., two adjacent feeds and two adjacent speeds) where new observations should be taken.

---

[1] The factor $f_{4,n}$ is used to convert a range to an estimate of the standard deviation.

The recommendations are derived by comparing the calculated effects with two standard errors of the effect:

1. If the absolute value of an effect is greater than or equal to the two standard errors, the effect is judged significant, i.e.,

   If $|EFFECT| \geq 2SE$

   then the EFFECT is judged significant.

2. If the absolute value of an effect is less than two standard errors, the effect is judged not significant, i.e.,

   If $|EFFECT| < 2SE$,

   then the EFFECT is judged not significant.

When one or more effects are judged significant, a new set of operating conditions is recommended by the program (i.e., a new phase) in accordance with a decision table. The decision table for minimizing Cu is given in Table 3.1. To maximize the production rate (Pr), the negative of Pr is minimized. Hence the same table is used by the program with the production rates replaced by their negatives.

3.3 Response Surface and Regression Analysis

Regression analysis is a technique for estimating the parameters of an equation relating a response variable to a set of independent variables. The resulting equation is called a regression equation. In the MACHOP program two response variables, the cost per piece and the production rate, are considered and regression equations are developed for each. The two independent variables are the feed (F) and the cutting speed (V).

The regression equation is used to predict the response (y) for the feeds and speeds in the region where the data were collected. Five different forms of the prediction equation are considered:

(3.1) $y = b_0 + b_1 \ln V + b_2 \ln F$

(3.2) $y = b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F$

(3.3) $y = b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln V)^2$

(3.4) $y = b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln F)^2$

(3.5) $y = b_0 + b_1 \ln V + b_2 \ln F + b_3 \ln V \cdot \ln F + b_4 (\ln V)^2 + b_5 (\ln F)^2$

Table 3.1 Decision Table for Minimization of Cost*

Significance and Direction of Effects			Action				
Speed(V)	Feed(F)	Interaction (V×F)	Reobserve same settings	Inc. Speed	Decr. Speed	Inc. Feed	Decr. Feed
0	0	0	*				
P	0	0			*		
N	0	0		*			
0	P	0					*
0	N	0				*	
P	P	0			*		*
N	P	0		*			*
P	N	0			*	*	
N	N	0		*		*	
0	0	P	If $\overline{y}_1$ is min., decr. speed and feed; if $\overline{y}_2$ is min., incr. speed and feed; if $\overline{y}_3$ is min., incr. speed and decr. feed; if $\overline{y}_4$ is min., decr. speed and incr. feed.				
0	0	N					
P	0	P			*	*	
P	0	N			*		*
N	0	P		*			*
N	0	N		*		*	
0	P	P		*			*
0	P	N				*	*
0	N	P			*	*	
0	N	N		*		*	
P	P	P			*		*
P	P	N			*		*
P	N	P			*	*	
P	N	N			*	*	
N	P	P		*			*
N	P	N		*			*
N	N	P		*		*	
N	N	N		*		*	

*P(N) indicates a significant positive (negative) effect; A 0 indicates the effect is not significant.

The natural logarithmic transformation of feed and speed was deemed appropriate on the basis of the work of Ermer and Wu [8] and the experience gained in analyzing RIA shop data. The program can be easily modified to use other transformations. One of the equations 3.1 - 3.5 is selected depending on the number of data points available and the number of levels of the feeds and speeds through the logic depicted in Figure 3.2.

The general methodology of the regression program is briefly explained in Section 3.3.1 for m independent variables and n observations. An understanding of this section is not necessary for use of the program. Section 3.3.2 contains a discussion of the regression calculations for phase 1, cycle 1.

3.3.1 General Methodology

A multiple regression equation may be expressed in the following form:

$$y - \bar{y} = \beta_1 (x_1 - \bar{x}_1) + \beta_2 (x_2 - \bar{x}_2) + \ldots + \beta_m (x_m - \bar{x}_m) + e,$$

where $\bar{y}$ and $\bar{x}$ are sample averages.

Given the set of observations:

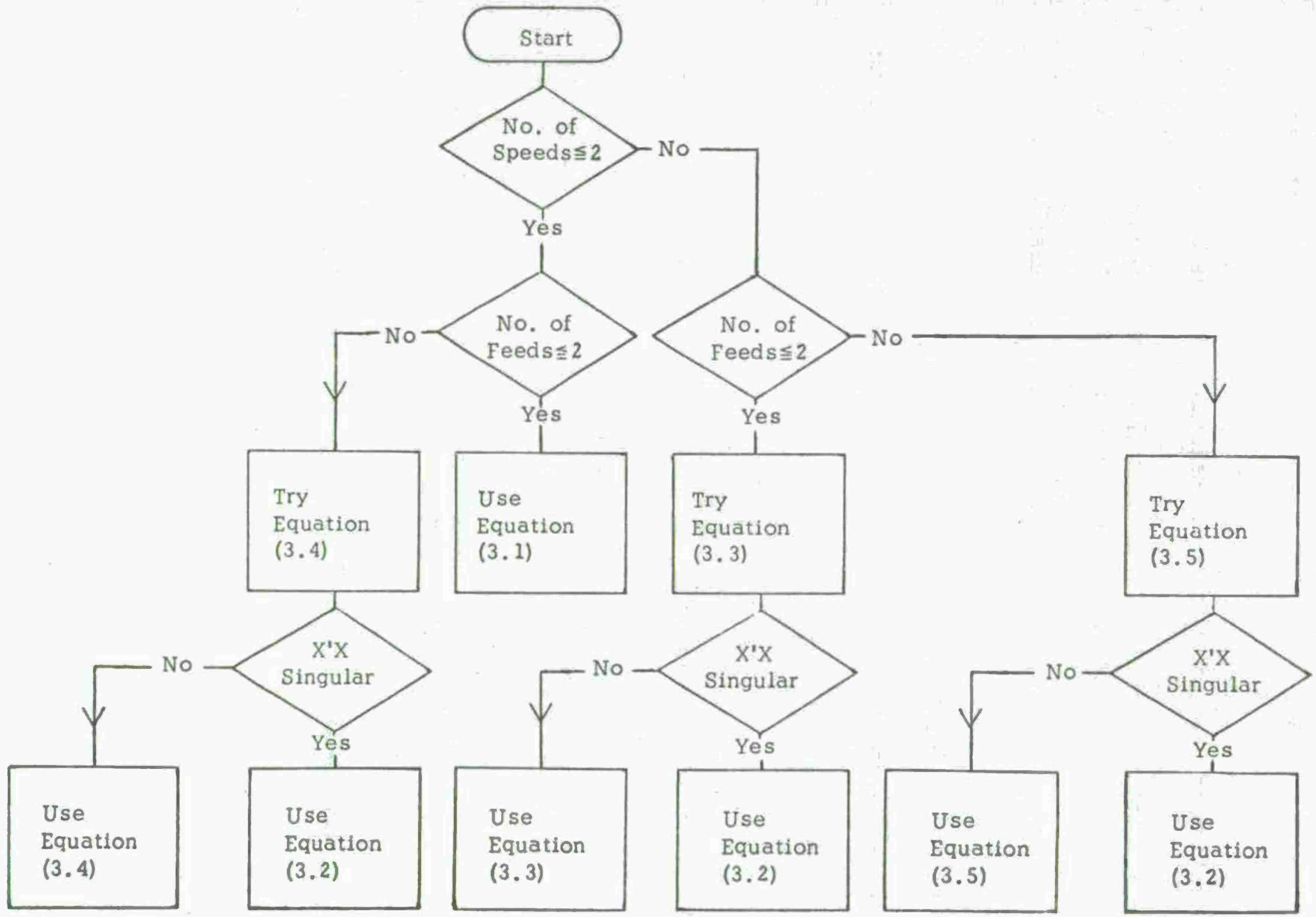
$$\begin{array}{cccc} x_{11} & x_{21} \ldots x_{m1} & y_1 \\ x_{12} & x_{22} \ldots x_{m2} & y_2 \\ \vdots & \vdots \quad \vdots & \vdots \\ x_{1n} & x_{2n} \ldots x_{mn} & y_n \end{array},$$

the X matrix is defined as

$$X = \begin{bmatrix} (x_{11} - \bar{x}_1) & (x_{21} - \bar{x}_2) \ldots (x_{m1} - \bar{x}_m) \\ (x_{12} - \bar{x}_1) & (x_{22} - \bar{x}_2) \ldots (x_{m2} - \bar{x}_m) \\ \vdots & \vdots \qquad \vdots \\ (x_{1n} - \bar{x}_1) & (x_{2n} - \bar{x}_2) \ldots (x_{mn} - \bar{x}_m) \end{bmatrix},$$

where

$$\bar{x}_i = \sum_{j=1}^{n} x_{ij}/n.$$



Selection of the Regression Equation

Figure 3.2

The $\underline{b}$ vector contains the unknown coefficients

$$\underline{b} = \begin{bmatrix} b_1 \\ b_2 \\ \cdot \\ \cdot \\ b_m \end{bmatrix}$$

and the $\underline{y}$ vector is calculated from the dependent variable observations by

$$\underline{y} = \begin{bmatrix} (y_1 - \overline{y}) \\ (y_2 - \overline{y}) \\ \vdots \\ (y_n - \overline{y}) \end{bmatrix} ,$$

where

$$\overline{y} = \sum_{j=1}^{n} y_j / n .$$

The least squares estimates of the unknown coefficients are

$$\underline{b} = (X'X)^{-1} X'\underline{y},$$

and the resulting prediction equation is

$$y = \overline{y} + b_1(x_1 - \overline{x}_1) + \ldots + b_m(x_m - \overline{x}_m) .$$

The analysis of variance table is given in Table 3.2.

Table 3.2 Analysis of Variance (ANOVA)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Total	n - 1	$\underline{y}'\underline{y}$		
Regression	m	$\underline{b}'(X'\underline{y})$	$\frac{\underline{b}'(X'\underline{y})}{m}$	$\frac{\underline{b}'(X'\underline{y})(n-1-m)}{m[\underline{y}'\underline{y}-\underline{b}'(X'\underline{y})]}$
Residual	n - 1 - m	$\underline{y}'\underline{y}-\underline{b}'(X'\underline{y})$	$\frac{\underline{y}'\underline{y}-\underline{b}'(X'\underline{y})}{n-1-m}$	

The significance of the resultant regression may be tested by an F test. Draper and Smith [5] state that the equation should not be considered a satisfactory predictor unless the F value is at least 4 times greater than the test statistic $F_{(m,n-1-m,1-\alpha)}$, where α is the significance level for the test.

The ratio (regression sum of squares)/(total sum of squares), denoted R^2, is a measure of the "goodness" of fit of the regression equation. An $R^2 = 1$ indicates a perfect fit of the data to the function, while $R^2 = 0$ indicates $b_1 = b_2 = \ldots = b_m = 0$. The variance, σ^2, is estimated by the mean square of the residuals.

3.3.2 Illustration of Regression Calculations for Phase 1, Cycle 1

To illustrate the regression methodology we consider the cost per piece prediction for phase 1, cycle 1. For phase 1, cycle 1, the following information is available $(m = 2, n = 4)$:

$$
\begin{array}{lllll}
V_1 & F_1 & NPT_1 & NTC_1 & NT_1 \\
V_2 & F_2 & NPT_2 & NTC_2 & NT_2 \\
W_3 & F_3 & NPT_3 & NTC_3 & NT_3 \\
V_4 & F_4 & NPT_4 & NTC_4 & NT_4
\end{array}
$$

where

V = speed (rpm),

F = feed (ipr),

NPT = no. of parts produced,

NTC = no. of tool changes, and

NT = total production time in minutes.

The logarithm of the feed (ln F) and of the speed (ln V) are the independent variables. The X matrix is

$$
X = \begin{bmatrix} (\ln V_1 - \overline{\ln}\, V) & (\ln F_1 - \overline{\ln}\, F) \\ \vdots & \vdots \\ (\ln V_4 - \overline{\ln}\, V) & (\ln F_4 - \overline{\ln}\, F) \end{bmatrix} ,
$$

where $\overline{\ln}$ denotes the averages of the logarithms.

The $\underline{b}$ vector is

$$\underline{b} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} .$$

The $\underline{y}$ vector is determined from the equations in Section 3.1 by

$$\underline{y} = \begin{bmatrix} y_1 - \bar{y} \\ y_2 - \bar{y} \\ y_3 - \bar{y} \\ y_4 - \bar{y} \end{bmatrix} .$$

The $\underline{b}$ vector is given by

$$\underline{b} = (X'X)^{-1}X'\underline{y} .$$

The prediction equation is given in the form

$$y = \bar{y} + b_1(\ln V - \overline{\ln} V) + b_2(\ln F - \overline{\ln} F) .$$

The ANOVA table is calculated according to Table 3.2 using the expressions given above.

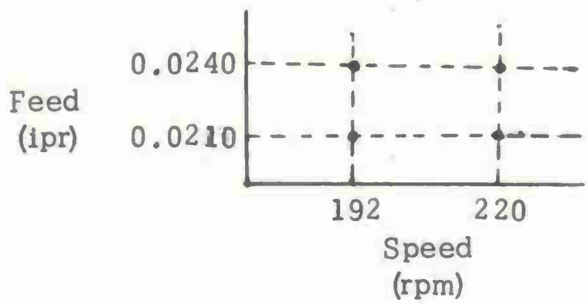
The MACHOP output contains an analysis of variance (ANOVA) table, the coefficient of multiple regression (R^2), the regression coefficients, their t values and the standard deviations for both the cost per piece and the production rate. Predictions of the cost per piece and the production rate are made for all feeds and speeds within one level of the extremes of the feeds and speeds where observations have been taken.

4. Use of MACHOP

The MACHOP program incorporates evolutionary operation and response surface-regression analysis to determine the optimal machining conditions for single-operation and multiple-operation (numerically controlled) processes. It is intended for use by managers or foremen directly concerned with the operation of individual machining processes.

4.1 Collecting Data for MACHOP

To simplify the collection of data in the shop, observations are always taken in cycles--a set of four observations at two adjacent feeds and two adjacent speeds. For example, if the feeds and speeds selected are (0.0210 ipr, 0.0240 ipr) and (192 rpm, 220 rpm), respectively, then data is collected at the following feed-speed combinations:



The MACHOP committee, composed of the foreman, the appropriate technical personnel and the machine operator, selects an initial set of operating conditions (two adjacent speeds and two adjacent feeds) for the machining operation under study. Before collecting data for the MACHOP program, trial runs should be made at each of the four feed-speed combinations to insure machinability under these conditions. If problems are encountered during trial runs at any of these four feed-speed combinations, a new set of four points should be selected, omitting the feed-speed combinations where problems were encountered. Trial runs should be made at these feed-speed combinations. This process is continued until four feed-speed combinations (at two adjacent feeds and two adjacent speeds) have been selected. Each feed-speed combination is then run for one shift of operation, and the following information is collected:

1. the number of parts produced,
2. the number of tool edges used for each tool type, and
3. the production time.[1]

---

[1]Actual machining, work piece handling and tool handling time.

The quality of the parts being machined should always be observed, and if at any time the operator feels the produced parts are in danger of not meeting standards, he should stop taking data at this feed and speed combination.

If data collection is discontinued at any feed-speed combination during a production run, a decision must be made concerning the use of the data already collected at this point. If the number of parts machined is sufficient to give accurate measures of the performance indices, the results can be used for input to the MACHOP program, even though a full shift of data has not been collected. If problems of workpiece accuracy are encountered or if it becomes apparent that scrap or tool breakage costs will exceed other potential gains during a production run prior to obtaining a sufficient number of parts, a new set of four feed-speed combinations should be selected. After collecting data at each of the four combinations and recording this information on the forms provided, the data is summarized and submitted to the MACHOP program. (Sample data collection forms are given in Appendix C, and a sample summary form is given in Figure G.1 of Appendix G.)

4.2 Analysis of the MACHOP Output

Sample MACHOP outputs appear in Figures 5.1 - 5.3. Each output gives the following information on separate pages:

a. Input information such as feed-speed limits, labor and overhead rates, tool costs, and prior estimates of standard deviations of the response variables (if any).

b. The specified feed-speed environment represented "graphically."

c. The cumulative input data and the computed responses (cost per piece and production rate).

d. A table of the computed responses for this phase and cycle.

e. Evolutionary operation calculations for both the cost per piece and production rate responses.

f. A recommended set of operating conditions for the next experiment (which may be identical to the current set), based on the cost per piece analysis.

g. A graphical representation of the operating conditions recommended in f.

h. The recommended set of operating conditions for the next experiment (which may be identical to the current set), based on the production rate analysis.

i. A graphical representation of the operating conditions recommended in h.

j. The results of the regression analysis and the accompanying analysis of variance table for the cost per piece analysis.

k. The results of the regression analysis and the accompanying analysis of variance table for the production rate analysis.

ℓ. The predicted response surfaces for cost/piece and production rate calculated from the respective prediction equations.

The output information in a, b, c and d should be reviewed for detection of any input errors. If any recording and/or transcription errors are noted, the input should be corrected and resubmitted to the MACHOP program. If it is determined that any of the data were collected under abnormal operating conditions, new data should be collected at these points. The results should then be resubmitted to the MACHOP program.

If the output information in a, b, c and d appears acceptable, the remainder of the output e-ℓ should be examined. Parts f, g, h, i, and ℓ are of particular interest to production personnel. Analysis of these results should allow a decision to be made concerning operating conditions for the next set of observations. (The other parts (e, j, and k) give additional details concerning the computations.) If the results and recommendations seem to be reasonable, the data should be collected at the set of points suggested by the MACHOP program. After the data have been collected, the above procedure is again followed. This process continues until MACHOP committee decides that sufficient data have been collected in order to determine optimal operating conditions.

The MACHOP recommendations should be treated as possible courses of action. The final decision rests with the MACHOP committee. If the committee decides to collect additional data, the following rules must be observed. The new set of observations must be taken either at the same four points (another cycle in the current phase) or at another rectangular pattern of adjacent points (a new phase). (A more complete discussion of phases and cycles was given in Section 3.2.1.) We suggest the movement be restricted to feed-speed combinations immediately adjacent to the previous feed-speed combinations. Either speed or feed or both may be varied at one time.

4.3 Scope of Application

The MACHOP routines can be used for single operation as well as multiple-operation (numerically controlled) processes.

For multiple-operation (non-numerically controlled) machine tools, data must be collected on all the cutting tools. In addition, one operation of the machine must be selected for the initial study, since only one set of feeds and speeds can be varied at a time. The selectionof this particular operation is important. In general, it should be the operation which has the greatest potential for improvement. This will often be the operation requiring the longest time. After this operation has been optimized, another operation can be selected for study. Sample data collection forms are given in Appendix C.

For numerically controlled processes a different problem is encountered. In this case the feeds and speeds for the operations are pre-programmed. However, the feeds and speeds can be adjusted by overrides. The optimization program is conducted through the use of these overrides in order to avoid reprogramming. Again a rectangular pattern is used, now in terms of percentage feed and speed overrides. Increments of five percent seem reasonable. If analysis of the data collected indicates that either the speed or feed increment should be adjusted beyond its presently programmed limits, consideration should be given to reprogramming the tape. At this point the relationship of the various speeds and feeds should also be discussed. Whenever the tape is changed, the MACHOP program must be restarted. That is, all previous data should be removed, and Phase 1 should begin again. The only information which can be used from the previous output are the estimates of the standard deviations and the costs. The estimates of the standard deviations from the last output should be submitted as prior estimates of the standard deviations. For numerically controlled processes, data is recorded on the same form as for multiple-operation processes. However instead of recording only feeds and speeds, the feed and speed overrides are also recorded.

4.4 Data Handling System

During the initial set-up of the problem (phase 1, cycle 1), the necessary data such as speed and feed environments must be recorded. Once this is accomplished, all succeeding cycles use the same input with the addition of a new set of observations and punched output from the previous cycle.

Once the initial information is given, less than five minutes per cycle will be required for data recording and preparation. Consequently, no elaborate data handling system is considered necessary for this process. A volume of four new cards per cycle is not sufficient to justify elaborate equipment. The most effective method for accomplishing this is for the individual directly interested with the process (ultimately the machinist) to be responsible for preparing the data sheets for forwarding to the data processing unit for key punching.

5. MACHOP Analysis of RIA Data

In this section the results of the MACHOP analysis of the turning operation (recoil cylinder, Part No. 10895646) on a Monarch lathe are given. The details of this particular operation are given in Table 2.5. A summary of the data collected is given in Table 5.1. For this machining operation the responses variables (cost per piece and production rate) are calculated from the production data as explained in Section 3.1. In addition to the input information required by the MACHOP program, a prior estimate of the standard deviation of the cost per piece of 0.60 dollars was specified, based on observations made during the initial phases of the study.[1] No estimate was made of the standard deviation of the production rate.

The data and output information for phase 1, cycle 1 are given in Figures 5.1a - 5.1ℓ. The cost analysis (Figure 5.1f) indicates that the factor feed was significant. Since no prior estimate of the production rate standard deviation was supplied, the EVOP analysis indicates none of the factors was significant. The response surface-regression analysis (Figure 5.1ℓ) was in general agreement with the EVOP analysis, so phase 2 was initiated. The feeds and speeds recommended by the EVOP cost per piece analysis (Figure 5.1f) were used for phase 2, cycle 1.

The MACHOP output for phase 2, cycle 1 is given in Figures 5.2a - 5.2ℓ. Based on the new data, a three variable regression equation was fitted. (See Section 3.3 for details.) Neither of the resulting EVOP analyses (Figures 5.2f and 5.2h) indicated that any factor was significant. Consequently, another cycle of data was taken for phase 2.

The MACHOP output for phase 2, cycle 2 appears in Figures 5.3a - 5.3ℓ. The EVOP analysis of the cost per piece and production rate results (Figures 5.3f and 5.3h) again indicates that none of the effects are significant. However, the predictions of cost per piece and production rate in response surface-regression (Figure 5.3ℓ) indicate the same direction toward the optimum. On the basis of these results, we could take another cycle of data for phase 2 or begin phase 3. We recommend beginning phase 3 of the study at either of the following sets of feed-speed combinations:

Speed	Feed		Speed	Feed
166	0.0210		166	0.0240
166	0.0240	or	166	0.0270
192	0.0210		192	0.0240
192	0.0240		192	0.0270

However, before beginning this phase, a trial run should be made at each of the new combinations to insure acceptable machining results.

Comparison of the predicted costs in Figure 5.3ℓ gives an indication of the potential for cost reduction through optional selection of feeds and speeds.

[1] Note that an estimate of the standard deviation is not required.

Table 5.1 Summary of RIA Data

	Date	Speed	Feed	No. of Parts	Time	No. of Tool Edges	Comments
1)	6/12/73	192	0.0187	18	410	18	None
2)	6/13/73	220	0.0210	20	440	44	Inserts break in half or chip. The out of round condition seems to contribute to insert breakage as I ran 2 pieces on one insert because they were fairly straight and had trouble running one piece with 2 inserts when the piece was extremely out of round.
3)	6/27/73	255	0.0187	11	267	29	None
4)	6/28/73	192	0.0210	14	377	18	Chips are still too tight. Tips of inserts are chipping at times depending on out of round condition of piece.
5)	6/29/73	220	0.0189	15	393	15	Good chips. Finish real good considering the condition of the pieces.
6)	7/5/73	192	0.0168	14	434	17	None
7)	7/10/73	220	0.0168	13	396	23	Tips of inserts are chipping easily on irregular pieces. Finish is poor as insert breaks down at about 3/4 of the way down the piece. Chips are small and tight.
8)	7/17/73	255	0.0168	10	217	17	None
9)	7/18/73	255	0.0210	14	357	31	Inserts break down about 1/4 way across cut. Finish is horrible.
10)	8/3/73	192	0.0187	14	374	16	None
11)	8/6/73	220	0.0187	15	394	17	Inserts break down 1/3 of the way through cut. Finish is very rough. (1 insert broke on end of piece so was able to use replaced edge on next piece.)
12)	8/7/73	220	0.0187	9	228	15	None
13)	8/16/73	192	0.0187	8	214	16	None
14)	8/17/73	220	0.0187	13	381	20	Finish was real good even for first time pieces done with one insert edge, but on third piece, insert had a tendency to break down 1/3 of the way across.

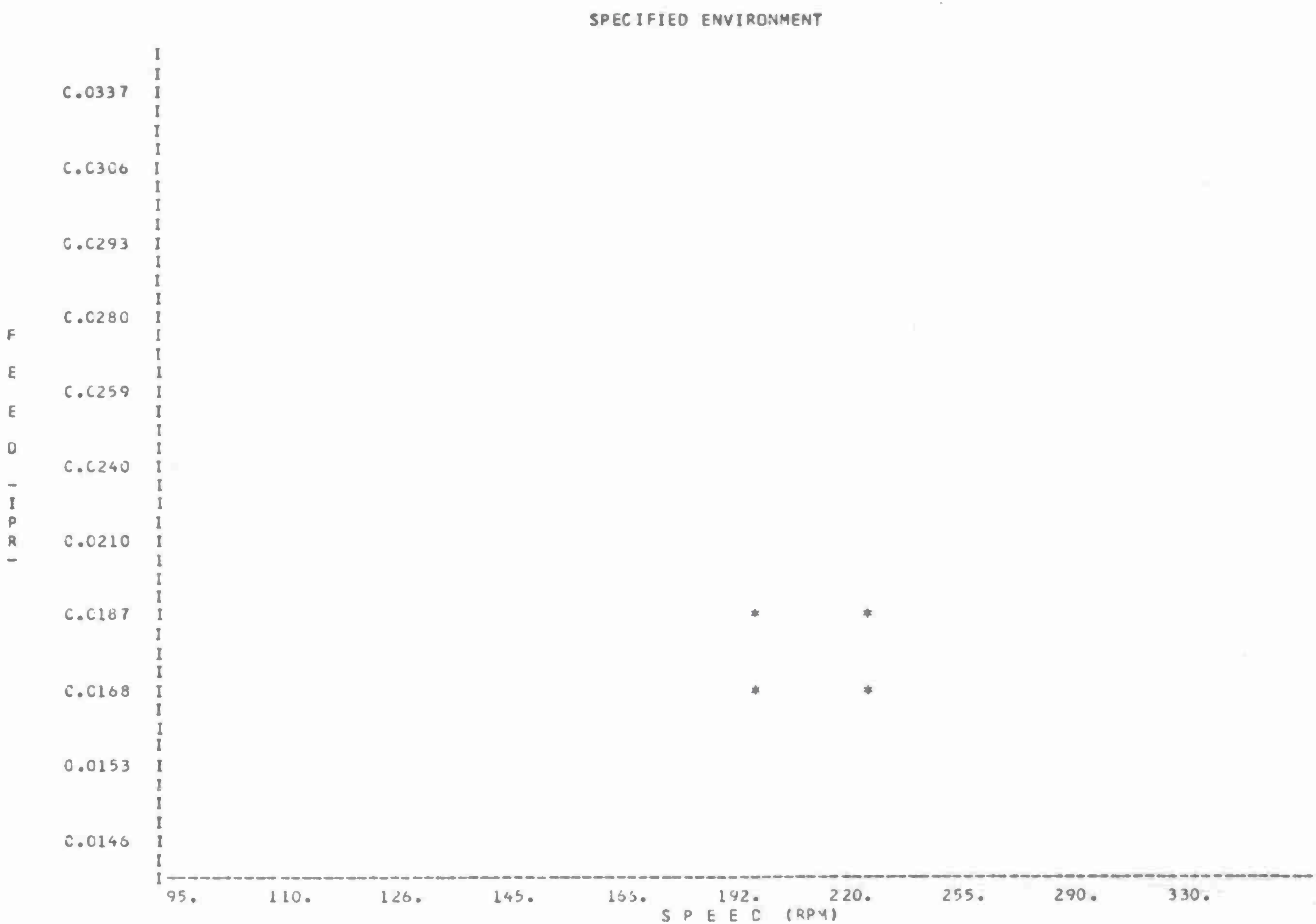
M A C H O P

TURNING OPERATION ON A MONARCH LATHE-- RECOIL CYLINDER, PART NO. 10895646

PHASE IS	1
CYCLE IS	1
TYPE OF PROCESS IS	1 SINGLE
SPEED-FEED LIMITS NOT SPECIFIED	
LABOR-OVERHEAD ($/MIN)	0.3000
COST STD. DEV. EST. IS	0.6000
P.R. STD. DEV. EST. IS NOT SPECIFIED	
NUMBER OF TOOLS IS	1
SPECIFIED TOOL COST/EDGE	0.4200
NUMBER OF SPEEDS IS	10
NUMBER OF FEEDS IS	11

a.

Figure 5.1 MACHOP Output for Phase 1, Cycle 1



b.

Figure 5.1 (continued)

INPUT VALUES AND COMPUTED RESPONSES

SPEED	FEED	PARTS	TIME	TOOL-EDGES (1) (11)	(2) (12)	(3) (13)	(4) (14)	(5) (15)	(6) (16)	(7) (17)	(8) (18)	(9) (19)	(10) (20)	COST ($/PIECE)	PROD RATE (PIECES/MIN)
192.	0.0168	14.	434.	17.										9.81	0.0323
220.	0.0187	15.	393.	15.										8.28	0.0382
220.	0.0168	13.	396.	23.										9.88	0.0328
192.	0.0187	18.	410.	18.										7.25	0.0439

c.

Figure 5.1 (continued)

TABLE OF RESPONSES

FEED (IPR)		192.		220.
0.0187	COST =	7.25	COST =	8.28
	PROD. RT. =	0.0439	PROD. RT. =	0.0382
0.0168	COST =	9.81	COST =	9.88
	PROD. RT. =	0.0323	PROD. RT. =	0.0328

S P E E D (RPM)

d.

Figure 5.1 (continued)

EVOLUTIONARY OPERATION ANALYSIS
PHASE 1 CYCLE 1

CALCULATION OF AVERAGES

	COST				PRODUCTION RATE			
OPERATING CONDITIONS								
SPEED (RPM)	192.	220.	220.	192.	192.	220.	220.	192.
FEED (IPR)	0.0168	0.0187	0.0168	0.0187	0.0168	0.0187	0.0168	0.0187
PREVIOUS CYCLE SUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PREVIOUS CYCLE AVERAGE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NEW OBSERVATIONS	9.81	8.28	9.88	7.25	0.0323	0.0382	0.0328	0.0439
DIFFERENCES	-9.81	-8.28	-9.88	-7.25	-0.0323	-0.0382	-0.0328	-0.0439
NEW SUMS	9.81	8.28	9.88	7.25	0.0323	0.0382	0.0328	0.0439
NEW AVERAGES: Y(I)	9.81	8.28	9.88	7.25	0.0323	0.0382	0.0328	0.0439

CALCULATION OF STANDARD DEVIATIONS

PREVIOUS AVERAGE S	0.6000	0.0
NEW S = RANGE * F4,N	0.0	0.0
RANGE	2.6282	0.0116
NEW SUM S	0.0	0.0
NEW AVERAGE S = NEW SUM S/2	0.0	0.0

CALCULATION OF 2 S.E. LIMITS:

FOR NEW EFFECTS	1.2000	0.0

e.

Figure 5.1 (continued)

COST ANALYSIS

THE EFFECT OF SPEED IS 0.5491 --- NOT SIGNIFICANT ---

THE EFFECT OF FEED IS -2.0791 *** -- SIGNIFICANT -- ***

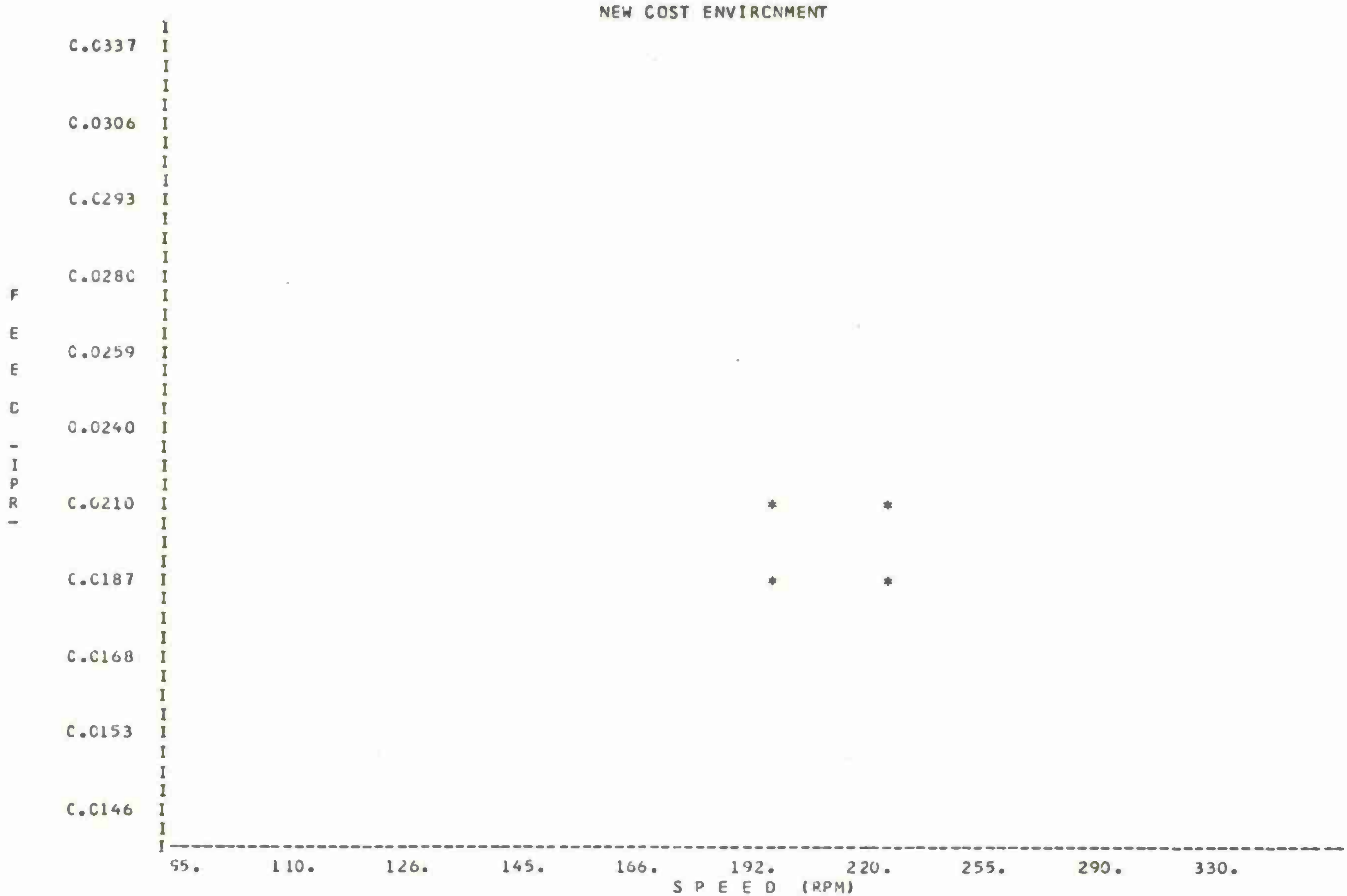
THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS 0.4776 --- NOT SIGNIFICANT ---

RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

4) SPEED = 192. FEED = 0.0210	2) SPEED = 220. FEED = 0.0210
1) SPEED = 192. FEED = 0.0187	3) SPEED = 220. FEED = 0.0187

f.

Figure 5.1 (continued)



g.

Figure 5.1 (continued)

PRODUCTION RATE ANALYSIS

NO PARAMETERS ARE SIGNIFICANT

THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

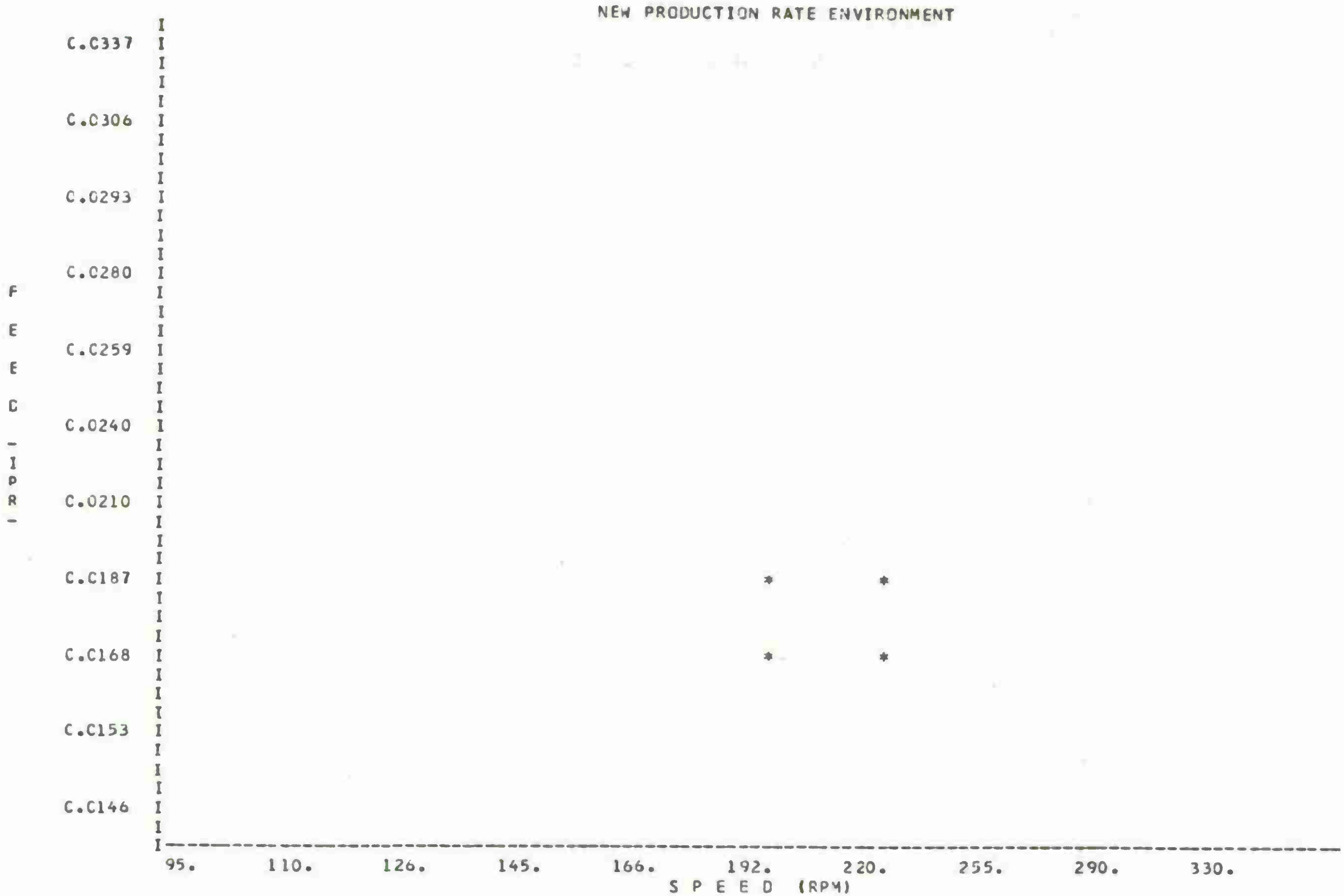
RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

```
4) SPEED =      192.        2) SPEED =      220.
   FEED =    0.0187            FEED =    0.0187


1) SPEED =      192.        3) SPEED =      220.
   FEED =    0.0168            FEED =    0.0168
```

h.

Figure 5.1 (continued)



i.

Figure 5.1 (continued)

MULTIPLE REGRESSION ON 2 VARIABLES WITH 4 OBSERVATIONS

COST EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	3	0.48522396E 01		
REGRESSION	2	0.46241693E 01	0.23120842E 01	0.10137596E 02
RESIDUAL	1	0.22807026E 00	0.22807026E 00	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.95299685E 00

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUBO =-0.90930115E 02		
BHAT(1)= 0.40335960 4E 01	T(1)= 0.11497908E 01	SD(1)= 0.35081120E 01
BHAT(2)=-0.194046631E 02	T(2)=-0.43535252E 01	SD(2)= 0.44572296E 01

THE PREDICTION EQUATION IS

PI = -90.9301 + 4.0336*LN(SPEED) + -19.4047*LN(FEED)

j.

Figure 5.1 (continued)

```
MULTIPLE REGRESSION ON  2 VARIABLES WITH     4 OBSERVATIONS


                                  PRODUCTION RATE EQUATION

                          ANOVA

SOURCE         DF          SS               MS               F

TOTAL           3      0.88719113E-04

REGRESSION      2      0.78781697E-04   0.39390841E-04   0.39638910E 01

RESIDUAL        1      0.99374156E-05   0.99374156E-05


COEFFICIENT OF MULTIPLE DETERMINATION (R**2) =      0.88799012E 00


          COEFFICIENTS                  T VALUES                     STANDARD DEV.

BSUBO    = 0.45743413E 00
BHAT( 1)=-0.189676855E-01         T( 1)=-0.81911176E 00          SD( 1)= 0.23156650E-01
BHAT( 2)= 0.792576671E-01         T( 2)= 0.26938515E 01          SD( 2)= 0.29421683E-01


THE PREDICTION EQUATION IS

PI =     0.4574 +    -0.0190*LN(SPEED) +     0.0793*LN(FEED)
```

k.

Figure 5.1 (continued)

PREDICTED COSTS
(PREDICTED PRODUCTION RATES)

FEED (IPR)	166.	192.	220.	255.
0.0210	4.65 (0.0543)	5.24 (0.0515)	5.79 (0.0489)	6.39 (0.0461)
0.0187	6.91 (0.0451)	7.49 (0.0423)	8.04 (0.0397)	8.64 (0.0369)
0.0168	8.98 (0.0366)	9.57 (0.0338)	10.12 (0.0313)	10.72 (0.0285)
0.0153	10.80 (0.0292)	11.39 (0.0264)	11.94 (0.0238)	12.53 (0.0210)

S P E E D (RPM)

l.

Figure 5.1 (continued)

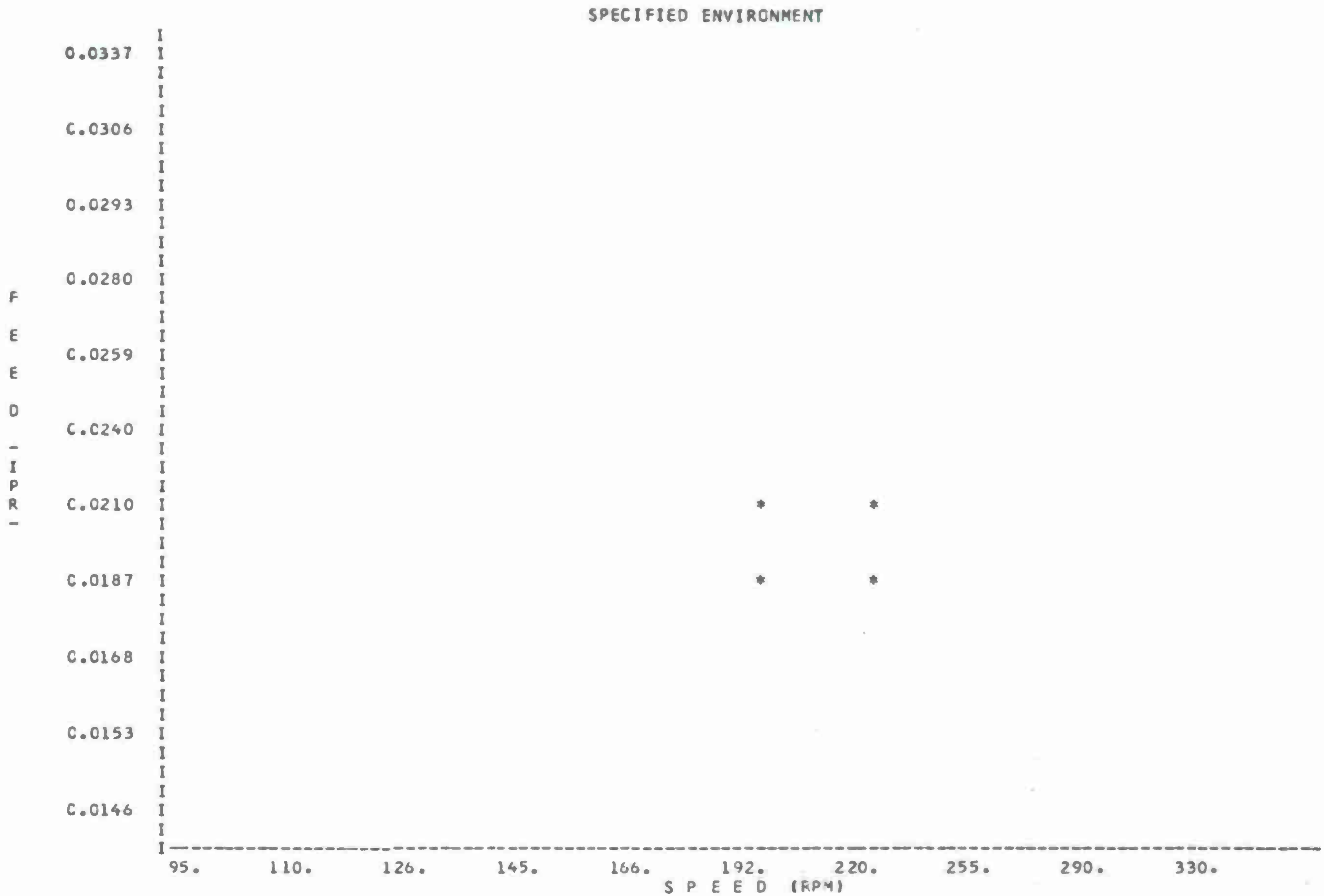
M A C H O P

TURNING OPERATION ON A MONARCH LATHE-- RECOIL CYLINDER, PART NO. 10895646

PHASE IS	2
CYCLE IS	1
TYPE OF PROCESS IS	1 SINGLE
SPEED-FEED LIMITS NOT SPECIFIED	
LABOR-OVERHEAD ($/MIN)	0.3000
COST STD. DEV. EST. IS	0.6000
P.R. STD. DEV. EST. IS NOT SPECIFIED	
NUMBER OF TOOLS IS	1
SPECIFIED TOOL COST/EDGE	0.4200
NUMBER OF SPEEDS IS	10
NUMBER OF FEEDS IS	11

a.

Figure 5.2 MACHOP Output for Phase 2, Cycle 1



b.

Figure 5.2 (continued)

INPUT VALUES AND COMPUTED RESPONSES

SPEED	FEED	PARTS	TIME	TOOL-EDGES (1) (11)	(2) (12)	(3) (13)	(4) (14)	(5) (15)	(6) (16)	(7) (17)	(8) (18)	(9) (19)	(10) (20)	COST ($/PIECE)	PROD RATE (PIECES/MIN)
192.	0.0168	14.	434.	17.										9.81	0.0323
192.	0.0187	18.	410.	18.										7.25	0.0439
220.	0.0168	13.	396.	23.										9.88	0.0328
220.	0.0187	15.	393.	15.										8.23	0.0382
192.	0.0187	8.	214.	16.										8.86	0.0374
220.	0.0210	20.	440.	44.										7.52	0.0455
220.	0.0187	15.	394.	17.										8.36	0.0381
192.	0.0210	14.	377.	18.										8.62	0.0371

C.

Figure 5.2 (continued)

TABLE OF RESPONSES

FEED (IPR)						
0.0210	COST =	8.62	COST =	7.52
	PROD. RT. =	0.0371	PROD. RT. =	0.0455
0.0187	COST =	8.86	COST =	8.36
	PROD. RT. =	0.0374	PROD. RT. =	0.0381
		192.		220.

S P E E D (RPM)

d.

Figure 5.2 (continued)

EVOLUTIONARY OPERATION ANALYSIS
PHASE 2 CYCLE 1

CALCULATION OF AVERAGES

	COST				PRODUCTION RATE			
OPERATING CONDITIONS								
SPEED (RPM)	192.	220.	220.	192.	192.	220.	220.	192.
FEED (IPR)	0.0187	0.0210	0.0187	0.0210	0.0187	0.0210	0.0187	0.0210
PREVIOUS CYCLE SUM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PREVIOUS CYCLE AVERAGE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NEW OBSERVATIONS	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371
DIFFERENCES	-8.86	-7.52	-8.36	-8.62	-0.0374	-0.0455	-0.0381	-0.0371
NEW SUMS	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371
NEW AVERAGES: Y(I)	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371

CALCULATION OF STANDARD DEVIATIONS

	COST	PRODUCTION RATE
PREVIOUS AVERAGE S	0.6000	0.0
NEW S = RANGE * F4,N	0.0	0.0
RANGE	1.3410	0.0083
NEW SUM S	0.0	0.0
NEW AVERAGE S = NEW SUM S/2	0.0	0.0

CALCULATION OF 2 S.E. LIMITS:

	COST	PRODUCTION RATE
FOR NEW EFFECTS	1.2000	0.0

e.

Figure 5.2 (continued)

```
                                   COST ANALYSIS

THE EFFECT OF SPEED IS                                 -0.8018  --- NOT SIGNIFICANT ---

THE EFFECT OF FEED IS                                  -0.5392  --- NOT SIGNIFICANT ---

THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS     -0.2928  --- NOT SIGNIFICANT ---

NO PARAMETERS ARE SIGNIFICANT

THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

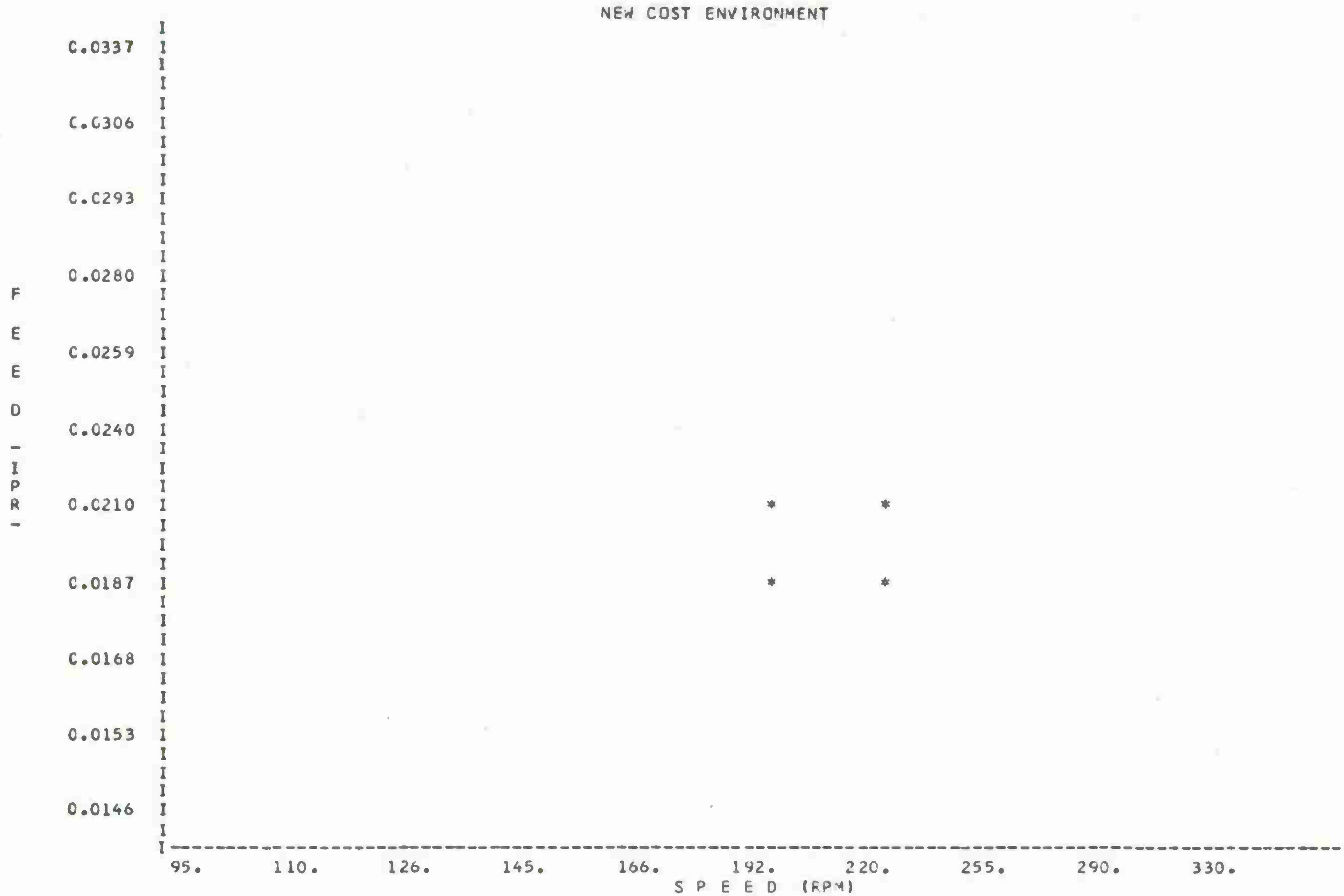

        RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

        4) SPEED =       192.          2) SPEED =       220.
           FEED =      0.0210             FEED =      0.0210


        1) SPEED =       192.          3) SPEED =       220.
           FEED =      0.0187             FEED =      0.0187
```

f.

Figure 5.2 (continued)



g.
Figure 5.2 (continued)

PRODUCTION RATE ANALYSIS

NO PARAMETERS ARE SIGNIFICANT

THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

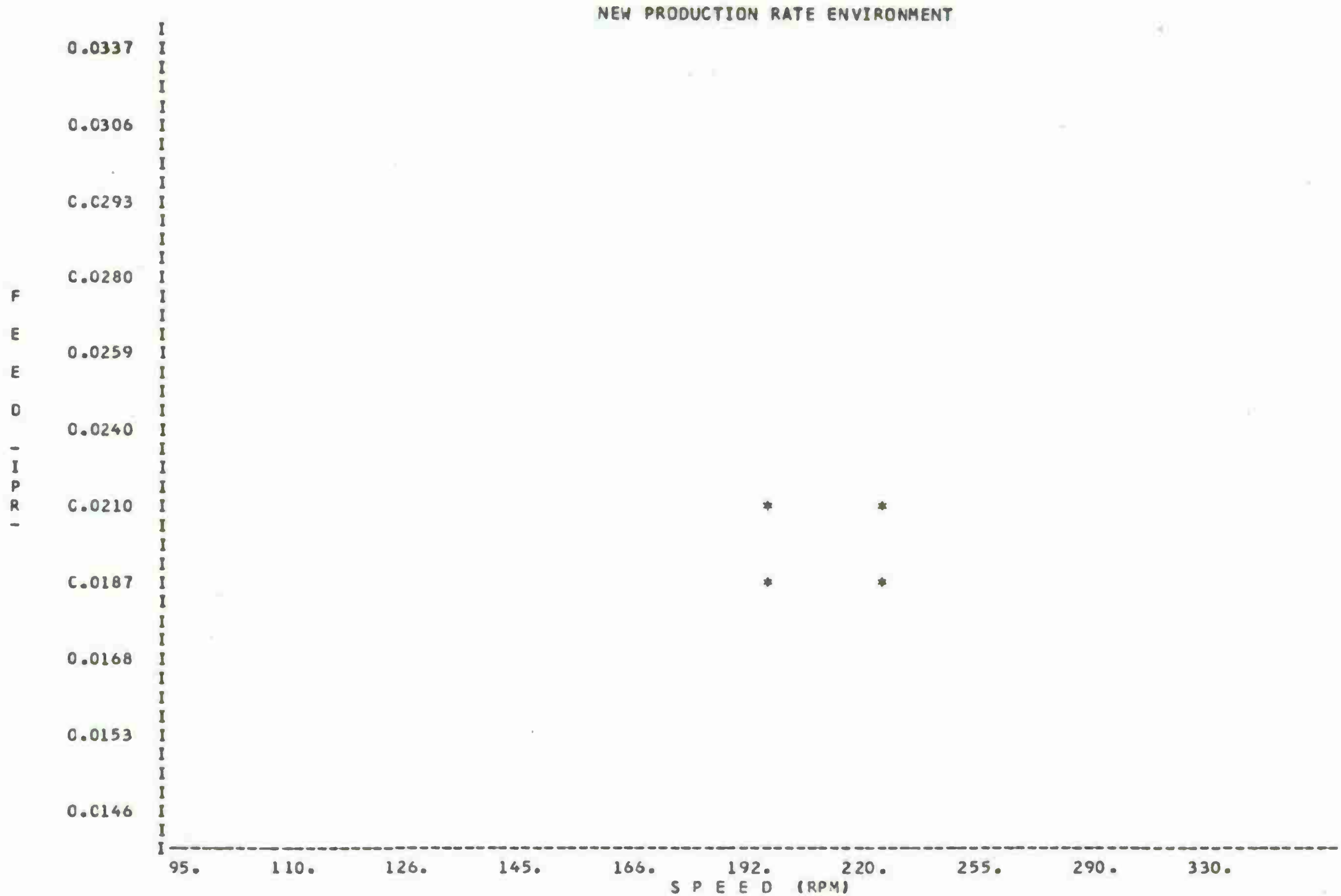
RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

```
4) SPEED =       192.        2) SPEED =       220.
   FEED  =     0.0210           FEED  =     0.0210


1) SPEED =       192.        3) SPEED =       220.
   FEED  =     0.0187           FEED  =     0.0187
```

h.

Figure 5.2 (continued)



i.
Figure 5.2 (continued)

MULTIPLE REGRESSION ON 3 VARIABLES WITH 8 OBSERVATIONS

COST EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	7	0.63046255E 01		
REGRESSION	3	0.30963936E 01	0.10321312E 01	0.12868528E 01
RESIDUAL	4	0.32082319E 01	0.80205798E 00	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.49113041E 00

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUB0 = 0.13522401E 02		
BHAT(1)=-0.678432846E 01	T(1)=-0.12261572E 01	SD(1)= 0.55330000E 01
BHAT(2)= 0.164294243E-02	T(2)= 0.64037174E 00	SD(2)= 0.25656072E-02
BHAT(3)=-0.147253323E 01	T(3)=-0.19548788E 01	SD(3)= 0.75326025E 00

THE PREDICTION EQUATION IS

PI = 13.5224 + -6.7843*LN(SPEED) + 0.0016*LN(FEED) + -1.4725*LN(SPEED)*LN(FEED)

j.

Figure 5.2 (continued)

MULTIPLE REGRESSION ON 3 VARIABLES WITH 8 OBSERVATIONS

PRODUCTION RATE EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	7	0.15110668E-03		
REGRESSION	3	0.77535209E-04	0.25845060E-04	0.14051676E 01
RESIDUAL	4	0.73571471E-04	0.18392864E-04	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.51311564E 00

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUBO = 0.52310526E-03		
BHAT(1)= 0.361627676E-01	T(1)= 0.13648310E 01	SD(1)= 0.26496135E-01
BHAT(2)=-0.111279078E-04	T(2)=-0.905573573E 00	SD(2)= 0.12286042E-04
BHAT(3)= 0.731847808E-02	T(3)= 0.20288677E 01	SD(3)= 0.36071721E-02

THE PREDICTION EQUATION IS

PI = 0.0005 + 0.0362*LN(SPEED) + -0.0000*LN(FEED) + 0.0073*LN(SPEED)*LN(FEED)

k.

Figure 5.2 (continued)

PREDICTED COSTS
(PREDICTED PRODUCTION RATES)

FEED (IPR)

FEED (IPR)	166.	192.	220.	255.
0.0240	6.91 (0.0459)	6.72 (0.0472)	6.55 (0.0484)	6.36 (0.0497)
0.0210	7.92 (0.0409)	7.76 (0.0420)	7.61 (0.0431)	7.45 (0.0443)
0.0187	8.79 (0.0366)	8.65 (0.0376)	8.53 (0.0385)	8.39 (0.0396)
0.0168	9.59 (0.0326)	9.48 (0.0335)	9.38 (0.0343)	9.27 (0.0352)
0.0153	10.30 (0.0291)	10.21 (0.0299)	10.12 (0.0306)	10.03 (0.0314)

S P E E D (RPM)

l.

Figure 5.2 (continued)

```
                         M A C H O P

     TURNING OPERATION ON A MONARCH LATHE-- RECOIL CYLINDER, PART NO. 10895646

PHASE IS                          2

CYCLE IS                          2

TYPE OF PROCESS IS                1 SINGLE

SPEED-FEED LIMITS NOT SPECIFIED

LABOR-OVERHEAD ($/MIN)       0.3000

COST STD. DEV. EST. IS       0.6000

P.R. STD. DEV. EST. IS NOT SPECIFIED

NUMBER OF TOOLS IS                1

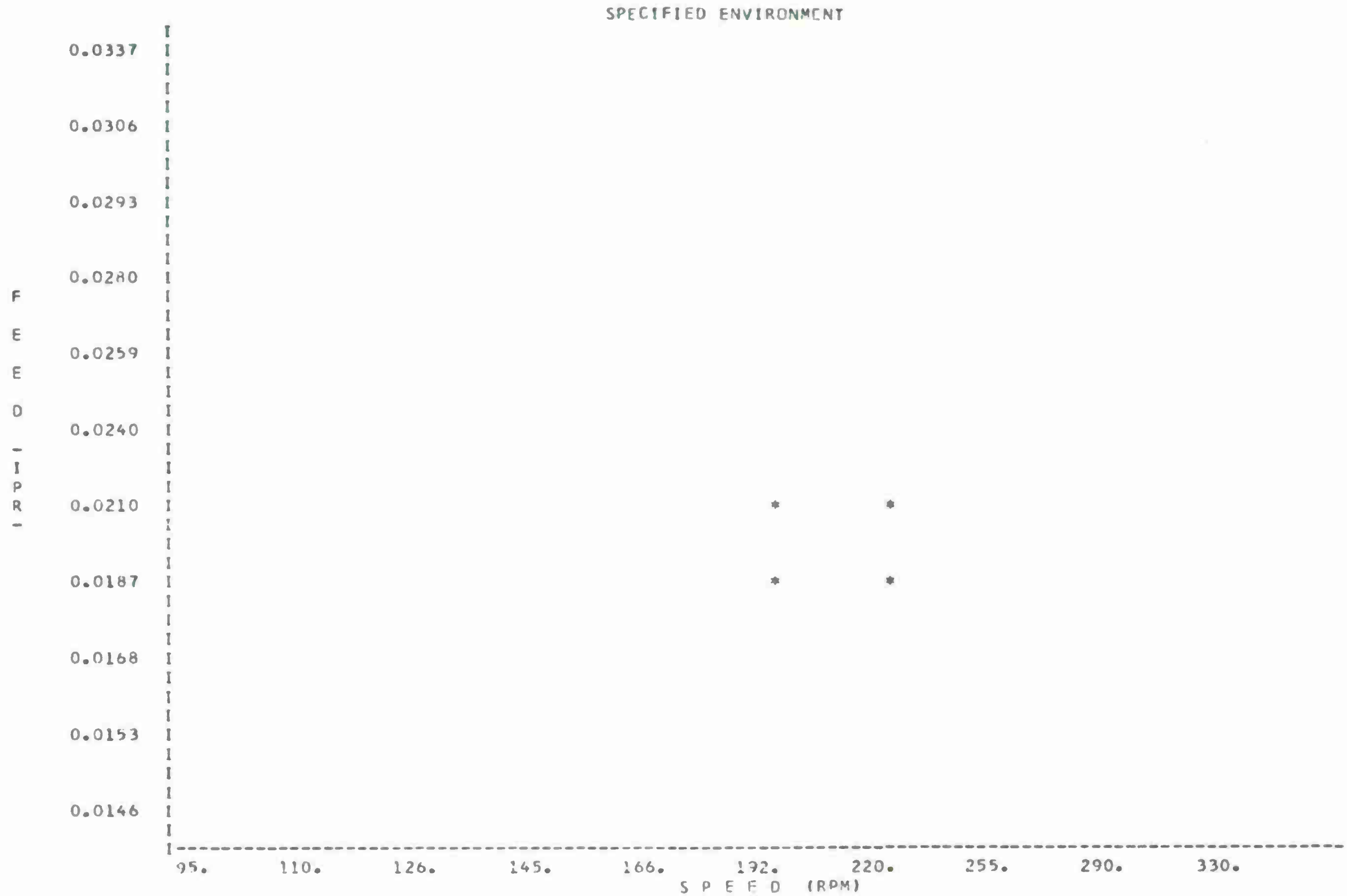
SPECIFIED TOOL COST/EDGE     0.4200

NUMBER OF SPEEDS IS              10

NUMBER OF FEEDS IS               11
```

a.

Figure 5.3 MACHOP Output for Phase 2, Cycle 2



b.
Figure 5.3 (continued)

INPUT VALUES AND COMPUTED RESPONSES

SPEED	FEED	PARTS	TIME	TOOL-EDGES (1) (11)	(2) (12)	(3) (13)	(4) (14)	(5) (15)	(6) (16)	(7) (17)	(8) (18)	(9) (19)	(10) (20)	COST ($/PIECE)	PROD RATE (PIECES/MIN)
192.	0.0168	14.	434.	17.										9.31	0.0323
192.	0.0187	18.	410.	18.										7.25	0.0439
220.	0.0168	13.	396.	23.										9.88	0.0328
220.	0.0187	15.	393.	15.										8.28	0.0382
220.	0.0210	20.	440.	44.										7.52	0.0455
192.	0.0187	8.	214.	16.										8.86	0.0374
220.	0.0187	15.	394.	17.										8.36	0.0381
192.	0.0210	14.	377.	18.										8.62	0.0371
192.	0.0187	14.	374.	14.										8.43	0.0374
220.	0.0210	6.	173.	47.										11.94	0.0347
220.	0.0187	13.	381.	20.										9.44	0.0341
192.	0.0210	6.	149.	18.										8.71	0.0403

c.

Figure 5.3 (continued)

TABLE OF RESPONSES

FEED (IPR)		192.	220.
0.0210	COST =	8.71	11.94
	PROD. RT. =	0.0403	0.0347
0.0187	COST =	8.43	9.44
	PROD. RT. =	0.0374	0.0341

S P E E D (RPM)

d.

Figure 5.3 (continued)

EVOLUTIONARY OPERATION ANALYSIS
PHASE 2 CYCLE 2

CALCULATION OF AVERAGES

	COST				PRODUCTION RATE			
OPERATING CONDITIONS								
SPEED (RPM)	192.	220.	220.	192.	192.	220.	220.	192.
FEED (IPR)	0.0187	0.0210	0.0187	0.0210	0.0187	0.0210	0.0187	0.0210
PREVIOUS CYCLE SUM	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371
PREVIOUS CYCLE AVERAGE	8.86	7.52	8.36	8.62	0.0374	0.0455	0.0381	0.0371
NEW OBSERVATIONS	8.43	11.94	9.44	8.71	0.0374	0.0347	0.0341	0.0403
DIFFERENCES	0.43	-4.42	-1.08	-0.09	-0.0000	0.0108	0.0040	-0.0031
NEW SUMS	17.30	19.46	17.79	17.33	0.0748	0.0801	0.0722	0.0774
NEW AVERAGES: Y(I)	8.65	9.73	8.90	8.66	0.0374	0.0401	0.0361	0.0387

CALCULATION OF STANDARD DEVIATIONS

	COST	PRODUCTION RATE
PREVIOUS AVERAGE S	0.0	0.0
NEW S = RANGE * F4,N	1.6479	0.0047
RANGE	4.8467	0.0139
NEW SUM S	3.2958	0.0095
NEW AVERAGE S = NEW SUM S/2	1.6479	0.0047

CALCULATION OF 2 S.E. LIMITS:

	COST	PRODUCTION RATE
FOR NEW EFFECTS	2.3305	0.0067

e.

Figure 5.3 (continued)

COST ANALYSIS

```
THE EFFECT OF SPEED IS                                  0.6576  --- NOT SIGNIFICANT ---

THE EFFECT OF FEED IS                                   0.4247  --- NOT SIGNIFICANT ---

THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS      0.4101  --- NOT SIGNIFICANT ---

NO PARAMETERS ARE SIGNIFICANT

THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

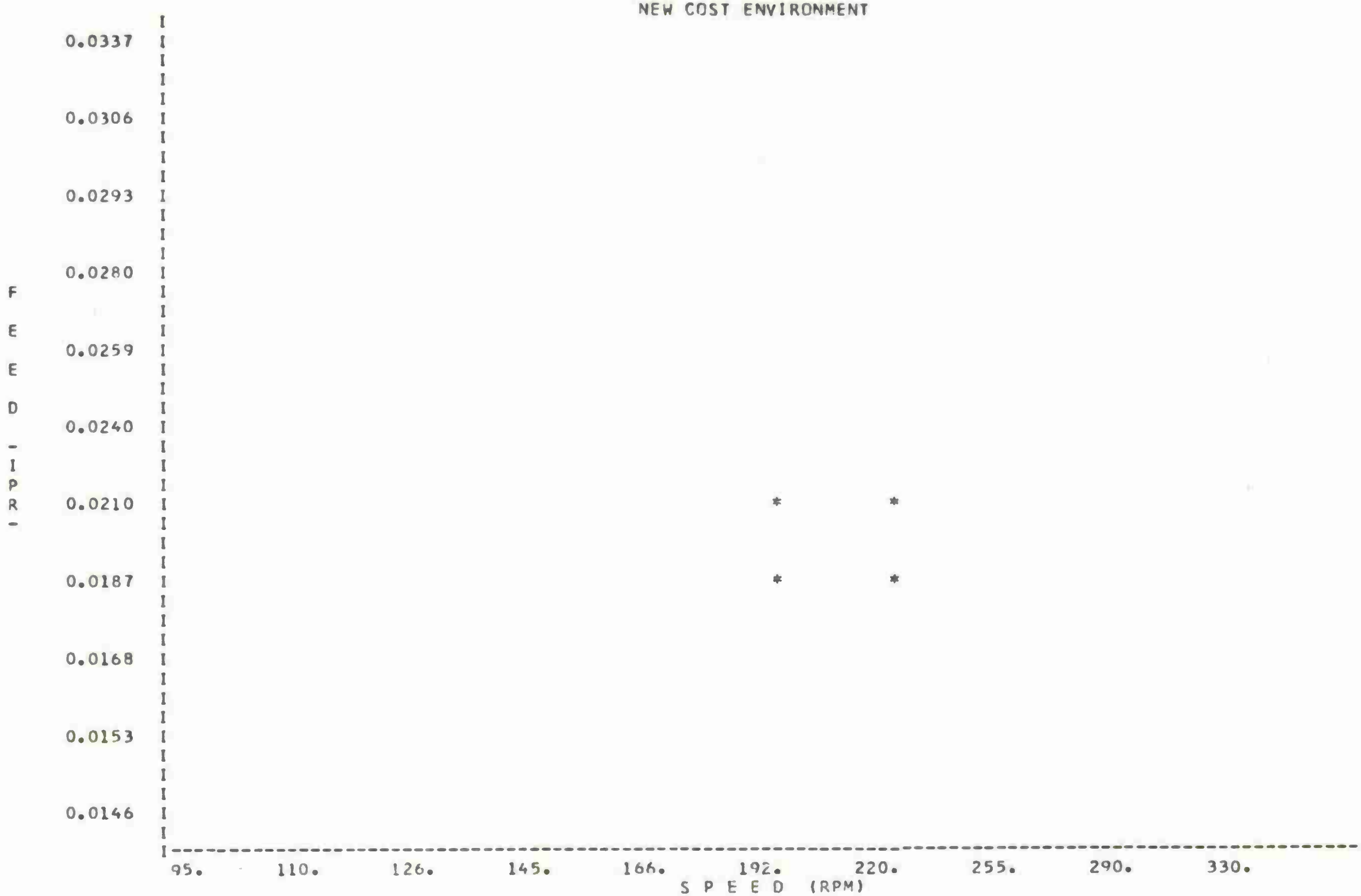

             RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

             4) SPEED =       192.         2) SPEED =       220.
                FEED =      0.0210            FEED =      0.0210


             1) SPEED =       192.         3) SPEED =       220.
                FEED =      0.0187            FEED =      0.0187
```

f.

Figure 5.3 (continued)



g.
Figure 5.3 (continued)

PRODUCTION RATE ANALYSIS

THE EFFECT OF SPEED IS	-0.0000	--- NOT SIGNIFICANT ---
THE EFFECT OF FEED IS	-0.0026	--- NOT SIGNIFICANT ---
THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS	-0.0013	--- NOT SIGNIFICANT ---

NO PARAMETERS ARE SIGNIFICANT

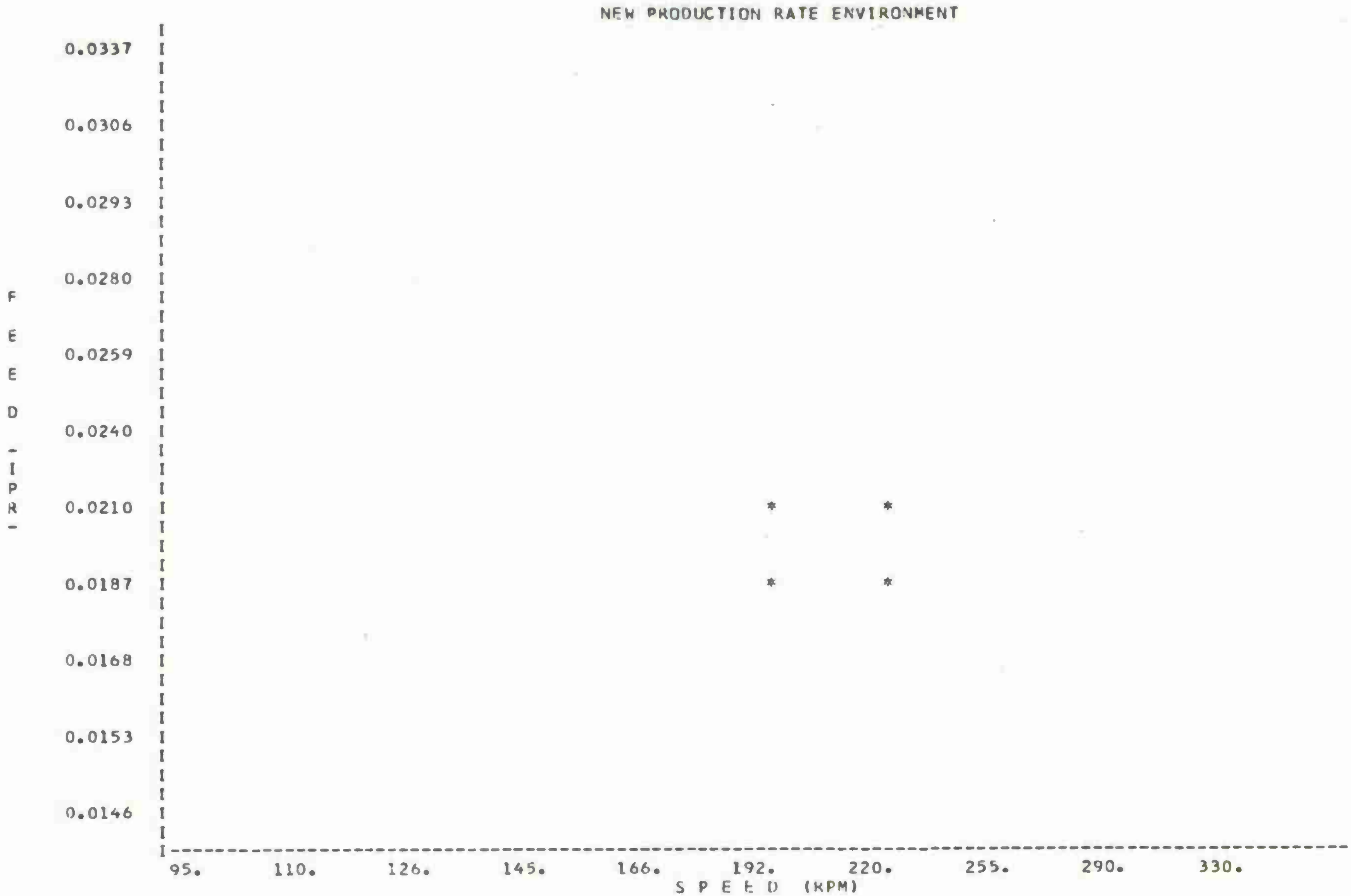
THE PREVIOUS SETTINGS SHOULD BE RE-EXAMINED

RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT POINTS:

4) SPEED =	192.	2) SPEED =	220.
FEED =	0.0210	FEED =	0.0210
1) SPEED =	192.	3) SPEED =	220.
FEED =	0.0187	FEED =	0.0187

h.

Figure 5.3 (continued)



i.
Figure 5.3 (continued)

MULTIPLE REGRESSION ON 3 VARIABLES WITH 12 OBSERVATIONS

COST EQUATION

ANOVA

SOURCE	DF	SS	MS	F
TOTAL	11	0.16933578E 02		
REGRESSION	3	0.15972290E 01	0.53240967E 00	0.27772433E 00
RESIDUAL	8	0.15336349E 02	0.19170437E 01	

COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = 0.94323158E-01

COEFFICIENTS	T VALUES	STANDARD DEV.
BSUBO =-0.72270166E 03		
BHAT(1)= 0.136644745E 03	T(1)= 0.45348996E 00	SD(1)= 0.30131812E 03
BHAT(2)=-0.178687088E 03	T(2)=-0.44082719E 00	SD(2)= 0.40534497E 03
BHAT(3)= 0.333668671E 02	T(3)= 0.43842232E 00	SD(3)= 0.76106674E 02

THE PREDICTION EQUATION IS

PI = -722.7017 + 136.6447*LN(SPEED) + -178.6871*LN(FEED) + 33.3669*LN(SPEED)*LN(FEED)

j.

Figure 5.3 (continued)

```
MULTIPLE REGRESSION ON  3 VARIABLES WITH   12 OBSERVATIONS


                         PRODUCTION RATE EQUATION

                    ANOVA

SOURCE         DF        SS                MS                F

TOTAL          11    0.18127424E-03

REGRESSION      3    0.54460019E-04    0.18153340E-04    0.11451931E 01

RESIDUAL        8    0.12681422E-03    0.15851765E-04


COEFFICIENT OF MULTIPLE DETERMINATION (R**2) =     0.30042887E 00


         COEFFICIENTS                 T VALUES                  STANDARD DEV.

BSUBO    =-0.13912010E 01
BHAT( 1)= 0.28804028CE 00      T( 1)= 0.33243382E 00      SD( 1)= 0.86645901E 00
BHAT( 2)=-0.369292736E 00      T( 2)=-0.31682760E 00      SD( 2)= 0.11655951E 01
BHAT( 3)= 0.743305087E-01      T( 3)= 0.33964205E 00      SD( 3)= 0.21884954E 00


THE PREDICTION EQUATION IS

PI =   -1.3912 +    0.2880*LN(SPEED) +   -0.3693*LN(FEED) +    0.0743*LN(SPEED)*LN(FEED)
```

k.

Figure 5.3 (continued)

PREDICTED COSTS
(PREDICTED PRODUCTION RATES)

FEED (IPR)	166.	192.	220.	255.
0.0240	6.09 (0.0414)	7.87 (0.0430)	9.53 (0.0445)	11.33 (0.0460)
0.0210	7.18 (0.0400)	8.30 (0.0401)	9.36 (0.0402)	10.50 (0.0404)
0.0187	8.12 (0.0387)	8.68 (0.0376)	9.21 (0.0366)	9.78 (0.0354)
0.0168	8.99 (0.0376)	9.03 (0.0353)	9.07 (0.0332)	9.12 (0.0309)
0.0153	9.75 (0.0366)	9.34 (0.0333)	8.95 (0.0302)	8.54 (0.0269)

S P E E D (RPM)

ℓ.

Figure 5.3 (continued)

6. Summary

Optimization of machining parameters, such as cutting speed and feed, is possible, in relation to time and costs, by use of this developed system and production machining data. This system, MACHOP (Machine Optimization Program), is applicable to analysis and control of single-operation as well as multiple-operation (numerically-controlled) machining. Simple formats are used to gather data from, and return computerized results to, production personnel. In application, two variables of the machining parameters may be adjusted independently or simultaneously, either manually by the machinist or by the numerical-control programmer, using small-step increments within the limits of the machine tool or the workpiece tolerances. Computation of results from data collected at the original adjusted machining parameters provides print-outs of four-point performance indices. These print-outs not only show time and cost performance at the machining parameters from which the data for computation has just been taken, but also give production settings which could improve performance. Subsequently, machining at adjoining machining parameters is tested and analyzed until the print-outs repeatedly indicate that the optimal conditions have been reached. Notably, the data system and computer program are simple, and general, enough to readily allow optimization of other machining parameters such as cutting fluids, work material selection, and tool material and geometry, as well as speeds and feeds.

The development of this system and related computer program has advanced the state-of-the-art of optimization in machining. In the past, optimization was restricted to optimizing an expanded Taylor Tool-Life equation, not optimization of the actual production machining operation itself, or required more adjustments of variables than were practicable in production operation.

7. Recommendations

It is recommended that this system and computer program be applied to analyze and control all major machining, and similar process, operations in which a large number of parts are produced in a single run or repetitive runs. It is also recommended that it be used to augment or replace time-study methods presently used to establish production standards; and, in particular, that it be applied to all new, major machining operations, and operations where new parameters, such as work material, cutting fluid, or tool material and geometry are introduced. Furthermore, it is strongly recommended that it be used to provide computerized print-outs of cutting tool-life and costs per workpiece for procurement and use of quality tools according to tool performance instead of merely tool price. Finally, it is recommended that this optimization procedure be used on other processes in which operations parameters may be adjusted to improve control of time and costs.

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Appendix A. Verification of Regression Modules of the PIM and MACHOP Programs

This appendix contains an output from a stepwise regression program, which was used to check the accuracy of the regression portion of the PIM program. A similar check was performed on the MACHOP program.

STEP NUMBER 5
VARIABLE ENTERED 1

MULTIPLE R 0.6104
STD. ERROR OF EST. 0.C172

ANALYSIS OF VARIANCE

	DF	SUM OF SQUARES	MEAN SQUARE	F RATIO
REGRESSION	5	0.001	0.000	0.356
RESIDUAL	3	0.001	0.000	

VARIABLES IN EQUATION

VARIABLE	COEFFICIENT	STD. ERROR	F TO REMOVE
(CONSTANT	-0.90118)		
SPEED 1	0.08087	0.60953	0.0176 (2)
FEED 2	0.96511	1.09571	C.7758 (2)
SPEDSQ 4	0.03636	0.12451	0.0853 (2)
FEEDSQ 5	-0.17757	0.279C3	C.4050 (9)
SPEDFD 6	-0.12478	0.12969	C.9257 (2)

VARIABLES NOT IN EQUATION

VARIABLE	PARTIAL CORR.	TOLERANCE	F TO ENTER

F-LEVEL OR TOLERANCE INSUFFICIENT FOR FURTHER COMPUTATION

SUMMARY TABLE

STEP NUMBER	VARIABLE ENTERED	VARIABLE REMOVED	MULTIPLE R	RSQ	INCREASE IN RSQ	F VALUE TO ENTER OR REMOVE	NUMBER OF INDEPENDENT VARIABLES INCLUDED
1	FEEDSQ 5		0.1999	0.0400	0.0400	0.2913	1
2	FEED 2		0.3584	0.1284	0.0885	0.6091	2
3	SPEDSQ 4		0.4038	0.1630	0.0346	0.2067	3
4	SPEDFD 6		0.6074	0.3689	0.2059	1.3048	4
5	SPEED 1		0.6104	0.3726	0.0037	0.0176	5

A.1 Sample Stepwise Regression Output

Appendix B. Simulation Program

This appendix contains a listing of the simulation program and a typical output. The instructions for using the program are given in the program as comments. This simulation program was developed for preliminary analysis of the PIM and MACHOP programs.

```
              IMPLICIT REAL*8 (A-H,O-Z)
              DIMENSION P(30),T(30),TP(30)
              DIMENSION F(30), V(30),PR(30),CU(30),PI(30)
              COMMON INT
      C
      C       NPT - IS THE NUMBER OF POINTS AT WHICH THE DATA IS TO BE GENERATED
      C
      C       Q - IS THE PERFORMANCE INDEX COEFFICIENT
      C
      C       INT - IS THE RANDOM SEED, A SEVEN DIGIT INTEGER
      C
              READ (5,12) NPT,Q,INT
      12      FORMAT (I10,F10.2,I10)
      C
      C       RLO - IS THE LABOR AND OVERHEAD IN $/MIN
      C
      C       TLC - IS THE TOOL COST IN $/EDGE
      C
              READ (5,20) RLO,TLC
      20      FORMAT (2F10.4)
              WRITE (6,30) RLO,TLC
      30      FORMAT (30X,'SIMULATION OF PRODUCTION DATA'///25X,'LABOR & OVERHEA
             1D COST = $',F5.2,' /MIN'//30X,'TOOL COST = $',F5.2,' /EDGE'//)
              READ (5,10) ((V(I),F(I)),I=1,NPT)
      10      FORMAT (2F10.4)
              DO 15 J = 1,NPT
              CALL SIM(J,F,V,NCT,KPT,TPD)
              P(J) = KPT
              T(J) = TPD
              TP(J) = NCT
      15      CONTINUE
              CALL        PERIND(P,T,TP,CU,PR,PI,Q,RLO,TLC,NPT)
              WRITE (6,24)
      24      FORMAT ('1',10X,'  SPEED    ','  FEED     ','  PARTS    ','  TOOL
             1 ','   TIME     ','   COST/     ','   PROD.     ','   PI-      '/
             213X,'(RPM)',5X,'(IPR)',17X,'CHANGES',14X,'PIECE',6X,'RATE',7X,'IND
             3EX'/)
              WRITE (6,25) ((V(I),F(I),P(I),TP(I),T(I),CU(I),PR(I),PI(I)),I=1,
             1NPT)
      25      FORMAT (10X,F10.1,F10.4,F10.1,F10.1,F10.1,F10.2,2F12.4/)
              RETURN
              END
```

```
FORTRAN IV G LEVEL  21                    RAND              DATE = 73361          17/31/11

              SUBROUTINE RAND(INT,IREAL)
              REAL*8 DREAL, DINT, DKEEP
        C        ARGUMENT NO 2 IN LIST IS A REAL IN THE CALL STATEMENT, BUT AN INTEGER
        C        IN THE SUBROUTINE
              DINT = INT
              DREAL = DINT * 16807.
              KEEP = DREAL / 2147483647.
              DKEEP = KEEP
              INT = DREAL - DKEEP * 2147483647.
              IREAL = (INT/128) + 1073741824
              RETURN
              END
```

```
FORTRAN IV G LEVEL  21                    UNINOM            DATE = 73361          17/31/11

              FUNCTION UNINOM(ERR,SIGMA)
              IMPLICIT REAL*8 (A-H,O-Z)
              COMMON INT
              CALL RAND(INT,REAL)
              XNORM =(REAL**0.19269651D0-(1-REAL)**0.19269651D0)/0.1306456D0
              UNINOM = ERR*SIGMA*XNORM
              RETURN
              END
```

```
FORTRAN IV G LEVEL  21                    PERIND            DATE = 73361          17/31/11

              SUBROUTINE PERIND(P,T,TP,CU,PR,PI,Q,RLO,TLC,NPT)
              IMPLICIT REAL*8(A-H,O-Z)
              DIMENSION P(30),T(30),TP(30)
              DIMENSION F(30), V(30),PR(30),CU(30),PI(30)
        C
              DO 100 I=1,NPT
              PR(I)=P(I)/T(I)
              CU(I)=(RLC*T(I)+TLC*TP(I))/P(I)
          100 PI(I)=(1.-Q)*PR(I)+(C/CU(I))
              RETURN
              END
```

```
      SUBROUTINE SIM(I,F,V,NTC,NTPT,TTPD)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION F(16),V(16)
      COMMON INT
C
C
C     IN THIS SUBROUTINE ALL THE PARAMETERS OF THE PRODUCTION PROCESS
C     ARE INITIALISED RATHER THAN TO BE READ BY A READ STATEMENT
C
C
C     TAYLOR'S TOOL LIFE CONSTANTS
C
      ALP = 0.3
      BETA = 0.2
      CONST = 400.0
C   XL -- LENGTH OF WORKPIECE
      XL = 47.5
C    D -- DIAMETER OF WORKPIECE
      D = 8.5
C   TCT -- TOOL CHANGING TIME
      TCT = 1.
C   TM -- MACHINING TIME / PIECE
      TM = XL/(V(I)*F(I))
C   TH -- HANDLING TIME / PIECE
      TH = 15.0
C   SHIFT -- TOTAL PRODUCTION TIME / SHIFT
      SHIFT = 420.0
C     ERR - IS THE RANDOM ERROR
      ERR = 0.20
      XV = 3.14159*D*V(I)/12.
      SIG = (DLOG(CONST)-BETA*DLOG(F(I))-DLOG(XV))/ALP
      ICOUNT = 0
      TIME = 0.
      PARTS = 0.
      WRITE (6,15) I,V(I),F(I)
   15 FORMAT ('1',10X,'FOR DAY',I2 /10X,'  SPEED=',F6.1,5X,'FEED=',F7.4/
     1/)
      WRITE (6,30) TM
   30 FORMAT ( '    MACHINING TIME FOR THIS SPEED & FEED',F7.2,' MIN'//)
   10 ICOUNT = ICOUNT + 1
      Y = UNINOM(ERR,SIG)
      TLIFE = DEXP(SIG+Y)
      PARTS1 = TLIFE/TM
      WRITE (6,20) ICOUNT,TLIFE,PARTS1
   20 FORMAT (' TOOL #',I3,5X,'LIFE=',F5.1,'MIN',5X,'# OF PARTS =',F5.2/
     1/)
      TIME1 = PARTS1*(TM+TH)+TCT
      PARTS = PARTS+PARTS1
      TIME = TIME+TIME1
      IF (TIME .LE. SHIFT) GO TO 10
      DIFF = TIME-SHIFT
      PARTMS = DIFF/(TM+TH)
      PARTS = PARTS-PARTMS
      WRITE (6,25)I,PARTS,ICOUNT,SHIFT
   25 FORMAT ('  SO FOR DAY',I3,/10X,F5.1,'PARTS ARE PRODUCED'/10X,I3,
     1 ' TOOLS ARE CHANGED DURING'/10X,F6.1,' MINUTES OF PRODUCTION TIME
     1'/)
      PARTS = PARTS + 0.25
      NTPT = PARTS
      TTPD = SHIFT
      NTC = ICOUNT
      RETURN
      END
```

SPEED= 192.0   FEED= 0.0187

MACHINING TIME FOR THIS SPEED & FEED 13.23 MIN

TOOL # 1	LIFE= 3.1MIN	# OF PARTS = 0.23
TOOL # 2	LIFE= 10.1MIN	# OF PARTS = 0.77
TOOL # 3	LIFE= 19.9MIN	# OF PARTS = 1.51
TOOL # 4	LIFE= 7.7MIN	# OF PARTS = 0.58
TOOL # 5	LIFE= 3.5MIN	# OF PARTS = 0.26
TOOL # 6	LIFE= 2.4MIN	# OF PARTS = 0.18
TOOL # 7	LIFE= 27.2MIN	# OF PARTS = 2.05
TOOL # 8	LIFE= 2.0MIN	# OF PARTS = 0.15
TOOL # 9	LIFE= 1.7MIN	# OF PARTS = 0.13
TOOL # 10	LIFE= 10.7MIN	# OF PARTS = 0.81
TOOL # 11	LIFE= 38.9MIN	# OF PARTS = 2.94
TOOL # 12	LIFE= 14.1MIN	# OF PARTS = 1.07
TOOL # 13	LIFE= 9.2MIN	# OF PARTS = 0.69
TOOL # 14	LIFE= 26.1MIN	# OF PARTS = 1.98
TOOL # 15	LIFE= 13.4MIN	# OF PARTS = 1.01

14.3PARTS ARE PRODUCED
15 TOOLS ARE CHANGED DURING
420.0 MINUTES OF PRODUCTION TIME

Appendix C. Data Collection Forms

Two types of data collection forms are given, one for single tool operations (Figure C.1) and the other for multiple tool operations (Figure C.2).

SINGLE TOOL MACHINE OPTIMIZATION STUDY FORM

Machine	Date	Stock Lot ID	Speed
Operator	Shift	Tool Material ID	Feed

Production Startup Time	Production Stop Time	Subtotals (minutes)

Total Production Time (minutes) ____________

Number of Pieces Produced (Tally) Total ____________

Number of Insert Edges Used (Tally) Total ____________

Comments:

Cost/edge ____________

Overhead and Labor Cost ____________

Figure C.1

MULTIPLE TOOL MACHINE OPTIMIZATION STUDY FORM

Sheet No.	Machine	Speed	Feed
Operator	Date	Shift	Stock Lot ID
Insert 1 ID	Insert 2 ID	Insert 3 ID	

Production Startup Time	Production Stop Time	Subtotals (minutes)

Total Production Time (minutes) ____________

Number of Pieces Produced

(Tally)

Total ____________

Number of Insert 1 Edges Used

(Tally)

Total ____________

Number of Insert 2 Edges Used

(Tally)

Total ____________

Number of Insert 3 Edges Used

(Tally)

Total ____________

Comments:

Cost/edge ____________

Overhead and Labor Cost ____________

Figure C.2

Appendix D. Analysis of the PIM Design Module

Following the determination of the optimum feed and speed based on a given set of experimental observations the next set of feed and speed combinations are chosen in the following manner:

1. In the event that the optimal point is not on a boundary, nine or fewer points are selected as follows. Initially a 3^2 design is selected with the previous optimal point as the center point, the distance between speeds is L_4 = number of usable speeds/4 and the distance between feeds is M_4 = number of usable feeds/4. Each point is checked with the boundary conditions to insure that it is feasible. If it is outside of the boundary condition, a replacement point is selected by moving the point in one step horizontally or vertically depending on the boundary condition. The procedure is repeated until a feasible point is selected. If this point does not duplicate another point already selected it is retained, otherwise it is discarded. Thus, fewer than nine points are possible.

2. In the event that the optimal point is on a boundary, five or fewer points are selected along the boundary with the previous optimal point in the middle. As in the previous case, each point picked is checked for feasibility and uniqueness. If the initial points selected are not feasible, they are moved in until they are feasible. In the process if some of the points duplicate other points already selected, they are discarded thus resulting in less than five points.

Appendix E. Carboloy Systems Computerized Machinability Program

This appendix contains the results obtained from General Electric's Carboloy computerized Machinability Program for the turning operation on the recoil cylinder. (See Table 2.5 for the job description.)

Access to this program may be made by acquisition of a G.E. terminal installation in the user's plant on a contractual basis or otherwise by sending the required information to the company for processing.

The program is based on historical machinability data and Taylor's tool life eqqation. If the tool material is entered into the program, the recommended feed and cutting speed for minimum cost and for maximum production rate will appear in the output data. If the feed and speed are entered, the recommended tool material will be indicated in the output data.

This approach has its limitations, for there are many variables which effect removal performance that cannot be accounted for in a generalized program. These variables include the condition and rigidity of the machine tool, type of tool holder, experience and ability of the machine operator, and the tool setting practice. Certainly, the program cannot be expected to predict precisely the optimum machining parameters. It may, however, serve as a good starting point to select the initial machine settings and/or tool material.

A copy of the program's output is given in Figure E.1. The Carboloy tool material, which was entered into the program by a G. E. representative and which was considered to be equivalent to the VR/Wesson, C5W Titanium Coated Carbide, was Carboloy Grade 350. The second choice was Grade 78. The equivalence of the entered grade to the one being used is questionable. The program recommended the following machining conditions:

Feed - 0.014 ipr,

Speed for Minimum Cost - 272 rpm, and

Speed for Maximum Production Rate - 358 rpm.

```
CUTTING FLUID ØN CARBØLOY MAY CAUSE TØØL FAILURE
DUE TØ THERMAL CRACKS. CHECK TØ MAKE SURE TØØLS ARE
WEARING ØUT, NØT CHIPPING ØR BREAKING
            IDENTIFICATIØN                            AISI 4140

            STARTING SURFACE CØNDITIØN                 HTR
            FINAL SURFACE FINISH                       250 MU. IN. 'AA'
            BRINELL HARDNESS                           252
            PART TØLERANCE                             .015 IN.
         CØØLANT                                       EMU
         MACHINE TØØL
            TYPE                                LATHE
            ØPERATIØN                           AXIAL TURN
            MØTØR HØRSEPØWER                            50
            SPINDLE SPEED LIMIT                         380
         CUTTING TØØL
            TØØL MATERIAL                         CARBØLØY
            GRADE                                      350
            2ND. CHØICE GRADE                          78
            SIDE CUTTING EDGE ANGLE                     30 DEG.
            NØSE RADIUS                               0.047 IN.
      ØUTPUT DATA
         SET UP
            STARTING DIA.                             8.500 IN.
            FEED                                       .014 IN./REV
            DEPTH ØF CUT                              0.125 IN.
            SPEED MIN. CØST                            272 RPM
            SPEED-MAX. PRØD.                           358 RPM
         TECHNICAL
            WEAR LAND                                  .030 IN.
            TØØL LIFE-MIN. CØST                          9 MIN.
            SPEED-MIN. CØST                            606 FPM
            H.P.-MIN. CØST                              11
            TØØL LIFE-MAX. PRØD.                         3 MIN.
            SPEED-MAX. PRØD.                           798 FPM
            H.P.-MAX. PRØD.                             14
IF CHIPPING ØF THE CUTTING EDGE ØCCURS USE SECØND CHØICE GRADE.
```

Figure E.1 Sample Carboloy Computerized Machinability Program Output

Appendix F. MACHOP Listing


```
      C
      C
      C                    MACHOP
      C
      C              (MACHINE OPTIMIZATION)
      C
      C
      C        THE MACHOP PROGRAM UTILIZES EVOLUTIONARY OPERATION (EVOP)
      C        AND REGRESSION ANALYSIS TO EXAMINE THE RESPONSE SURFACE OF
      C        MACHINING OPERATIONS TO DETERMINE THE OPTIMUM FEED-SPEED
      C        COMBINATIONS. TWO PERFORMANCE INDICIES, COST/PIECE AND
      C        PRODUCTION RATE ARE CONSIDERED AS RESPONSES.  FIRST THE
      C        PROGRAM PERFORMS AN EVOP ANALYSIS AND RECOMMENDS TWO SETS
      C        OF OPERATING CONDITIONS.  NEXT THE REGRESSION COEFFICIENTS
      C        FOR THE FOLLOWING EQUATION ( OR A REDUCED FORM OF IT ) ARE
      C        ESTIMATED
      C
      C        P.I. = B0 + B1*LN(SPEED) + B2*LN(FEED) + B3*LN(SPEED)**2
      C             + B4*LN(FEED)**2 + B5*LN(SPEED*FEED)
      C
      C        USING THESE RESULTS, THE PERFORMANCE INDICIES ARE PREDICTED
      C        FOR FEED - SPEED COMBINATIONS ADJACENT TO THOSE OBSERVED.
      C        THE PROGRAM IS APPLICABLE TO SINGLE-OPERATION AND
      C        MULTIPLE-OPERATION(NUMERICALLY CONTROLLED) MACHINING
      C        PROCESSES.
      C
      C
      C        REFERENCES ARE
      C
      C        BOX, G. & DRAPER, N.,  EVOLUTIONARY OPERATION  A STATISTICAL
      C           METHOD FOR INCREASING PRODUCTIVITY , JOHN WILEY & SONS,
      C           1969.
      C
      C        BURCHFIELD,P.B., MULTIPLE LINEAR REGRESSION ,'JOURNAL OF
      C           QUALITY TECHNOLOGY',VOL. 3,NO. 4,OCTOBER 1971.
      C
      C        DRAPER, N. & SMITH, H.,  APPLIED REGRESSION ANALYSIS ,
      C           JOHN WILEY & SONS, NEW YORK, 1968.
      C
      C
0001          COMMON /C101/SPEED(100),FEED(100),SPND(100),NSPD,NFD,ISP,IFD
0002          COMMON /C102/IPH,ICYC,SCYCLE,RLO,X(24,100),Y(2,100),NOBS,NCB1
             *,IOP,BSP,BFD,NTLC,TLC(20)
0003          COMMON /C103/DIFF(2,4),SUM(2,4),AVE(2,4),SUMS(2),AVES(2,2)
0004          COMMON /C107/IND(4),SMAX,SMIN,FMAX,FMIN
0005          DIMENSION B(5),TITLE(20),BCO(2),BP(2,5),IRR(2)
      C
      C        INPUT MAIN CONTROL CARD
      C
0006          WRITE(6,5999)
0007          IER=1
0008          READ(5,5004,END=9011,ERR=9012)TITLE
0009          WRITE(6,6000)TITLE
0010          READ(5,5001,END=9001,ERR=9002)
```

```
                 *IPH,ICYC,IOP,IMAX,NTLC,FLO,AVES(1,1),AVES(2,1),BSP,BFD
                  IF(IPH.GT.0)GO TO 601
                  WRITE(6,6001)IPH
                  IER=2
                  GO TO 602
         601      WRITE(6,6002)IPH
         602      IF(ICYC.GT.0)GO TO 603
                  WRITE(6,6003)ICYC
                  IER=2
                  GO TO 604
         603      WRITE(6,6004)ICYC
         604      IF(IOP.GT.0.AND.IOP.LT.4)GO TO 605
                  WRITE(6,6005)IOP
                  IER=2
         605      GO TO (606,607,608),IOP
         606      WRITE(6,6006)IOP
                  GO TO 609
         607      WRITE(6,6007)IOP
                  GO TO 609
         608      WRITE(6,6008)IOP
         609      IF(IMAX.NE.1)GO TO 610
                  WRITE(6,6009)
                  GO TO 611
         610      WRITE(6,6010)
         611      WRITE(6,6011)FLO
                  IF(AVES(1,1).LE.0.0)GO TO 612
                  WRITE(6,6012)AVES(1,1)
                  GO TO 613
         612      WRITE(6,6013)
         613      IF(AVES(2,1).LE.0.0)GO TO 6612
                  WRITE(6,6613)AVES(2,1)
                  GO TO 6614
        6612      WRITE(6,6615)
        6614      IF(IOP.NE.3)GO TO 628
                  IF(BSP.LE.0.0.OR.BFD.LE.0.0)GO TO 615
                  WRITE(6,6014)BSP,BFD
                  GO TO 628
         615      WRITE(6,6015)
                  IER=2
         628      IF(NTLC.EQ.0)NTLC=1
                  IF(NTLC.LT.1.OR.NTLC.GT.20)GO TO 747
                  WRITE(6,6024)NTLC
                  READ(5,5003,END=9009,ERR=9010)(TLC(I),I=1,NTLC)
                  DO 2276 I=1,NTLC
                  IF(TLC(I).LT.0)GO TO 2277
        2276      CONTINUE
                  WRITE(6,6029)(TLC(I),I=1,NTLC)
                  GO TO 614
        2277      IER=2
                  WRITE(6,5026)
                  GO TO 614
         747      IER=2
                  WRITE(6,6025)NTLC
         614      GO TO (616,617),IER
```

```
0064      617  WRITE(6,6016)
0065           CALL EXIT
          C
          C        INPUT SPEED ENVIRONMENT
          C
0066      616  READ(5,5002,END=9003,ERR=9004)NSPD
0067           IF(NSPD.LE.0.OR.NSPD.GT.100)GO TO 618
0068           WRITE(6,6018)NSPD
0069           GO TO 619
0070      618  WRITE(6,6019)NSPD
0071           GO TO 617
0072      619  READ(5,5003,END=9003,ERR=9004)      (SPEED(I),I=1,NSPD)
0073           DO 620 I=1,NSPD
0074           IF(SPEED(I).LE.0.0)GO TO 621
0075      620  CONTINUE
0076           GO TO 622
0077      621  WRITE(6,6020)
0078           GO TO 617
          C
          C        INPUT FEED ENVIRONMENT
          C
0079      622  READ(5,5002,END=9005,ERR=9006)NFD
0080           IF(NFD.LE.0.OR.NFD.GT.50)GO TO 623
0081           WRITE(6,6022)NFD
0082           GO TO 624
0083      623  WRITE(6,6021)NFD
0084           GO TO 617
0085      624  READ(5,5003,END=9005,ERR=9006)     (FEED(I),I=1,NFD)
0086           DO 625 I=1,NFD
0087           IF(FEED(I).LE.0.0)GO TO 626
0088      625  CONTINUE
0089           GO TO 627
0090      626  WRITE(6,6023)
0091           GO TO 617
          C
          C        INPUT LIMITS FOR SPEED AND FEED
          C
0092      627  IF(IMAX.EQ.1)READ(5,5003,END=9007,ERR=9008)SMAX,SMIN,FMAX,FMIN
0093           IF(SMAX.EQ.0.0)SMAX=SPEED(NSPD)
0094           IF(SMIN.EQ.0.0)SMIN=SPEED(1)
0095           IF(FMAX.EQ.0.0)FMAX=FEED(NFD)
0096           IF(FMIN.EQ.0.0)FMIN=FEED(1)
          C
          C        INSURE INPUT SPEEDS AND FEEDS ARE WITHIN DEFINED LIMITS
          C
0097           DO 7 J=1,NSPD
0098           IF (SPEED(J).LT.SMIN)GO TO 7
0099           IF(J.EQ.1)GO TO 8
0100           NSPD=NSPD-J+1
0101           DO 15 K=1,NSPD
0102           SPEED(K)=SPEED(J)
0103      15   J=J+1
0104           GO TO 8
0105      7    CONTINUE
```

```
01C6    8      DO 9 J=1,NSPD
01C7           IF(SPEED(J).GT.SMAX)GO TO 10
01C8    9      CONTINUE
01C9           GO TO 11
011C    10     NSPD=J
0111    11     DO 14 I=1,NFD
0112           IF (FEED(I).LT.FMIN)GO TO 14
0113           IF(I.EQ.1)GO TO 12
0114           NFD=NFD-I+1
0115           DO 16 J=1,NFD
0116           FEED(J)=FEED(I)
0117    16     I=I+1
0118           GO TO 12
0119    14     CONTINUE
012C    12     DO 13 I=1,NFD
0121           IF(FEED(I).GT.FMAX)GO TO 17
0122    13     CONTINUE
0123           GO TO 64
0124    17     NFD=I
        C
        C           PREPARE FOR E V O P ANALYSIS
        C
0125    64     CALL NUCYCL
        C
        C           IDENTIFY INPUT SPEED
        C
0126           DO 32 I=1,NSPD
0127           IF(X(1,NOB1).EQ.SPEED(I)) GO TO 33
0128    32     CONTINUE
0129    33     ISP=I
        C
        C           IDENTIFY INPUT FEED
        C
013C           DO 34 I=1,NFD
0131           IF(X(2,NOB1).EQ.FEED(I)) GO TO 35
0132    34     CONTINUE
0133    35     IFD=I
0134           IF(ISP.LT.IND(1))IND(1)=ISP
0135           ISPP1=ISP+1
0136           IF(ISPP1.GT.IND(2))IND(2)=ISPP1
0137           IF(IFD.LT.IND(3))IND(3)=IFD
0138           IFDP1=IFD+1
0139           IF(IFDP1.GT.IND(4))IND(4)=IFDP1
        C
        C           PERFORM THE E V O P ANALYSIS
        C
014C           CALL EVOP
        C
        C           PERFORM THE REGRESSION ANALYSIS
        C
0141           IF(IND(2)-IND(1)-1)41,42,43
0142    41     WRITE(6,48)
0143           GO TO 9033
0144    42     IREGS=0
```

```
          GO TO 44                                                    MAIN2170
    43    IREGS=1                                                     MAIN2180
    44    IF(IND(4)-IND(3)-1)41,45,46                                 MAIN2190
    45    IREGF=0                                                     MAIN2200
          GO TO 47                                                    MAIN2210
    46    IREGF=2                                                     MAIN2220
    47    IREG=1+IREGS+IREGF                                          MAIN2230
          IREG1=IREG                                                  MAIN2240
          DO 599 IGO=1,2                                              MAIN2250
          IREG=IREG1                                                  MAIN2260
          CALL REGRES(X,Y,NOBS,IREG,B0,B,IGO)                         MAIN2270
C                                                                     MAIN2280
C              PRINT PREDICTION EQUATION AND RESPONSE SURFACE PREDICTION MAIN2290
C                                                                     MAIN2300
          GO TO (1,2,3,4,5),IREG                                      MAIN2310
     1    WRITE(6,51)B0,B(1),B(2)                                     MAIN2320
          GO TO 6                                                     MAIN2330
     2    WRITE(6,52)B0,B(1),B(2),B(3),B(4)                           MAIN2340
          GO TO 6                                                     MAIN2350
     3    WRITE(6,53)B0,B(1),B(2),B(3),B(4)                           MAIN2360
          GO TO 6                                                     MAIN2370
     4    WRITE(6,54)B0,B(1),B(2),B(3),B(4),B(5)                      MAIN2380
          GO TO 6                                                     MAIN2390
     5    WRITE(6,55)B0,B(1),B(2),B(3)                                MAIN2400
     6    CONTINUE                                                    MAIN2410
          BOO(IGO)=B0                                                 MAIN2420
          IRR(IGO)=IREG                                               MAIN2430
          DO 589 I=1,5                                                MAIN2440
   589    BP(IGO,I)=B(I)                                              MAIN2450
   599    CONTINUE                                                    MAIN2460
          CALL REGPLT(BOO,BP,IND,IRR)                                 MAIN2470
C                                                                     MAIN2480
C              ERROR ANALYSIS                                         MAIN2490
C                                                                     MAIN2500
  9001    WRITE(6,9017)                                               MAIN2510
  9033    CALL EXIT                                                   MAIN2520
  9002    WRITE(6,9018)                                               MAIN2530
          GO TO 9033                                                  MAIN2540
  9003    WRITE(6,9019)                                               MAIN2550
          GO TO 9033                                                  MAIN2560
  9004    WRITE(6,9020)                                               MAIN2570
          GO TO 9033                                                  MAIN2580
  9005    WRITE(6,9021)                                               MAIN2590
          GO TO 9033                                                  MAIN2600
  9006    WRITE(6,9022)                                               MAIN2610
          GO TO 9033                                                  MAIN2620
  9007    WRITE(6,9023)                                               MAIN2630
          GO TO 9033                                                  MAIN2640
  9008    WRITE(6,9024)                                               MAIN2650
          GO TO 9033                                                  MAIN2660
  9009    WRITE(6,6027)                                               MAIN2670
          GO TO 9033                                                  MAIN2680
  9010    WRITE(6,6028)                                               MAIN2690
          GO TO 9033                                                  MAIN2700
```

```
0193      9011  WRITE(6,6030)
0194            GO TO 9033
0195      9012  WRITE(6,6031)
0196            GO TO 9033
          C
          C          FORMATS
          C
0197      48    FORMAT('1    *** ERROR ***  UNABLE TO DISTINGUISH SPEED/FEED ',
               *'COMBINATIONS')
0198      51    FORMAT(//'0',T10,'THE PREDICTION EQUATION IS'/'0  PI = ',F10.4,
               *' + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED)')
0199      52    FORMAT(//'0',T10,'THE PREDICTION EQUATION IS'/'0  PI = ',F10.4,
               *' + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED) + ',F10.4,
               *'*LN(SPEED)*LN(FEED)'/'0',T9,' + ',F10.4,'*LN(SPEED)**2')
0200      53    FORMAT(//'0',T10,'THE PREDICTION EQUATION IS'/'0  PI = ',F10.4,
               *' + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED) + ',F10.4,
               *'*LN(SPEED)*LN(FEED)'/'0',T9,' + ',F10.4,'*LN(SPEED)**2')
0201      54    FORMAT(//'0',T10,'THE PREDICTION EQUATION IS'/'0  PI = ',F10.4,
               *' + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED) + ',F10.4,
               *'*LN(SPEED)*LN(FEED)'/'0',T9,' + ',F10.4,'*LN(SPEED)**2 + ',
               *F10.4,'*LN(FEED)**2')
0202      55    FORMAT(//'0',T10,'THE PREDICTION EQUATION IS'/'0  PI = ',F10.4,
               *' + ',F10.4,'*LN(SPEED) + ',F10.4,'*LN(FEED) + ',F10.4,
               *'*LN(SPEED)*LN(FEED)')
0203      5001  FORMAT(5I3,T21,5F10.4)
0204      5002  FORMAT(I3)
0205      5003  FORMAT(8F10.4)
0206      5004  FORMAT(20A4)
0207      5999  FORMAT('1',T61,'M A C H O P')
0208      6000  FORMAT(//'0',T26,20A4)
0209      6001  FORMAT(//'0',T10,'PHASE IS',T35,I10,' *** ERROR ***')
0210      6002  FORMAT(//'0',T10,'PHASE IS ',T35,I10)
0211      6003  FORMAT('0',T10,'CYCLE IS ',T35,I10,' *** ERROR ***')
0212      6004  FORMAT('0',T10,'CYCLE IS',T35,I10)
0213      6005  FORMAT('0',T10,'TYPE OF PROCESS IS',T35,I10,' *** ERROR ***')
0214      6006  FORMAT('0',T10,'TYPE OF PROCESS IS',T35,I10,' SINGLE')
0215      6007  FORMAT('0',T10,'TYPE OF PROCESS IS',T35,I10,' MULTIPLE')
0216      6008  FORMAT('0',T10,'TYPE OF PROCESS IS',T35,I10,' NUMERICAL CONTROL')
0217      6009  FORMAT('0',T10,'SPEED-FEED LIMITS SPECIFIED')
0218      6010  FORMAT('0',T10,'SPEED-FEED LIMITS NOT SPECIFIED')
0219      6011  FORMAT('0',T10,'LABOR-OVERHEAD ($/MIN)',T35,F10.4)
0220      6012  FORMAT('0',T10,'COST STD. DEV. EST. IS',T35,F10.4)
0221      6013  FORMAT('0',T10,'COST STD. DEV. EST. IS NOT SPECIFIED')
0222      6014  FORMAT('0',T10,'BASE SPEED IS',T35,F10.4/'0',T10,
               *'BASE FEED IS',T35,F10.4)
0223      6015  FORMAT('0',T10,'BASE SPEED AND/OR FEED INCORRECTLY SPECIFIED')
0224      6016  FORMAT('0',T10,'*** PROGRAM TERMINATION DUE TO SPECIFIED ERROR',
               *' CONDITIONS ***')
0225      6018  FORMAT('0',T10,'NUMBER OF SPEEDS IS',T35,I10)
0226      6019  FORMAT('0',T10,'NUMBER OF SPEEDS IS',T35,I10,' *** ERROR ***')
0227      6020  FORMAT('0',T10,'SPECIFIED SPEEDS ARE L/E ZERO')
0228      6021  FORMAT('0',T10,'NUMBER OF FEEDS IS',T35,I10,' *** ERROR ***')
0229      6022  FORMAT('0',T10,'NUMBER OF FEEDS IS',T35,I10)
0230      6023  FORMAT('0',T10,'SPECIFIED FEEDS ARE L/E ZERO')
```

```
0231      6024  FORMAT('0',T10,'NUMBER OF TOOLS IS',T35,I10)
0232      6025  FORMAT('0',T10,'NUMBER OF TOOLS IS',T35,I10,' ***  ERROR  ***')
0233      6026  FORMAT('0',T10,'SPECIFIED TOOL COST NEGATIVE   ***  ERROR  ***')
0234      6027  FORMAT('1  ***  ERROR  ***      UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'TOOL COSTS MISSING')
0235      6028  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,' ON TOOL COST INPUT')
0236      6029  FORMAT('0',T10,'SPECIFIED TOOL COST/EDGE',(' ',T37,10F8.4))
0237      6030  FORMAT('1  ***  ERROR  ***      UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'TITLE CARD MISSING')
0238      6031  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,' ON TITLE CARD')
0239      6613  FORMAT('0',T10,'P.R. STD. DEV. EST. IS',T35,F10.4)
0240      6615  FORMAT('0',T10,'P.R. STD. DEV. EST. IS NOT SPECIFIED')
0241      9017  FORMAT('1  ***  ERROR  ***      UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'MAIN PROBLEM CARD MISSING')
0242      9018  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,' ON MAIN PROBLEM CARD')
0243      9019  FORMAT('1  ***  ERROR  ***      UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'INPUT SPEED PARAMETERS MISSING')
0244      9020  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,'ON INPUT SPEED PARAMETERS')
0245      9021  FORMAT('1  ***  ERROR  ***      UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'INPUT FEED PARAMETERS MISSING')
0246      9022  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,'ON INPUT FEED PARAMETERS')
0247      9023  FORMAT('1  ***  ERROR  ***      UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'INPUT SPEED/FEED LIMITS MISSING')
0248      9024  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,'ON INPUT SPEED/FEED LIMITS')
0249            END
```

```
FORTRAN IV G LEVEL  21                    NUCYCL               DATE = 74053          10/32/02

0001                SUBROUTINE NUCYCL
              C
              C
              C         SUBROUTINE NUCYCL IS USED FOR PROCESSING ALL PHASE/CYCLE
              C         COMBINATIONS.  NUCYCL PREPARES THE INPUT DATA FOR BOTH
              C         THE EVOP AND REGRESSION PROCESSES.
              C
              C
0002                DIMENSION TEMP(4,24)
0003                COMMON /C102/ IPH,ICYC,SCYCLE,RLD,X(24,100),Y(2,100),NOBS,NOB1
                   *,IOP,RSP,BFD,NTIC,TIC(20)
0004                COMMON /C103/DIFF(2,4),SUM(2,4),AVE(2,4),SUMS(2),AVES(2,2)
0005                COMMON /C107/IND(4),SMAX,SMIN,FMAX,FMIN
0006          702   SCYCLE=ICYC
0007                NTICP=NTIC+4
0008                DO 9 I=1,2
0009                AVES(I,2)=0.0
0010          9     SUMS(I)=0.0
              C
              C         INPUT NEW OBSERVATIONS
              C
0011                NOBS=1
0012          703   NOB1=NOBS+1
0013                NOB4=NOBS+3
0014                READ(5,5302,END=9017,ERR=9016) (X(J,NOBS),J=1,NTICP)
0015                IF(X(1,NOBS).EQ.0.12345)GO TO 701
0016                DO 66 J=NOB1,NOB4
0017          66    READ(5,5302,END=9015,ERR=9016)  (X(I,J),I=1,NTICP)
0018                NOBS=NOBS+4
0019                GO TO 703
              C
              C         INPUT THE DATA FROM THE PREVIOUS CYCLE
              C
0020          701   READ(5,5301,END=9011,ERR=9012)
                   *((SUM(J,I),I=1,4),SUMS(J),(AVE(J,I),I=1,4),AVES(J,2),J=1,2),
                   *(IND(I),I=1,4)
0021                IF(AVES(1,2).NE.0.0)AVES(1,1)=AVES(1,2)
0022                IF(AVES(2,2).NE.0.0)AVES(2,1)=AVES(2,2)
              C
              C         SORT POINTS INTO CORRECT SEQUENCE
              C
0023          9017  NOBS=NOBS-1
0024                NOB1=NOBS-3
0025                DO 45 I=1,4
0026                DO 45 J=1,NTICP
0027          45    TEMP(I,J)=X(J,NOB1+I-1)
0028                SPMI=TEMP(1,1)
0029                SPMA=TEMP(1,1)
0030                FDMI=TEMP(1,2)
0031                FDMA=TEMP(1,2)
0032                DO 10 I = 2,4
0033                IF(TEMP(I,1).LE.SPMI)SPMI=TEMP(I,1)
0034                IF(TEMP(I,1).GE.SPMA)SPMA=TEMP(I,1)
0035                IF(TEMP(I,2).LE.FDMI)FDMI=TEMP(I,2)
```

```
0036              IF(TEMP(I,2).GE.FDMA)FDMA=TEMP(I,2)
0037        10    CONTINUE
0038              DO 11 I = 1,4
0039              J=0
0040              IF (TEMP(I,1).EQ.SPMI.AND.TEMP(I,2).EQ.FDMI) J=1
0041              IF (TEMP(I,1).EQ.SPMA.AND.TEMP(I,2).EQ.FDMA) J=2
0042              IF (TEMP(I,1).EQ.SPMA.AND.TEMP(I,2).EQ.FDMI) J=3
0043              IF (TEMP(I,1).EQ.SPMI.AND.TEMP(I,2).EQ.FDMA) J=4
0044              IF( J.EQ.0) GO TO 15
            C
            C         CALCULATE THE RESPONSE VARIABLES
            C
0045              DO 11 K=1,NTLCP
0046              X(K,NOBI+J-1)=TEMP(I,K)
0047        11    CONTINUE
0048              DO 46 I=1,NOBS
0049              Y(2,I)=X(3,I)/X(4,I)
0050              Y(1,I)=FLO*X(4,I)
0051              DO 47 J=5,NTLCP
0052        47    Y(1,I)=Y(1,I)+X(J,I)*TLC(J-4)
0053        46    Y(1,I)=Y(1,I)/X(3,I)
            C
            C         PLOT THE INPUT POINTS
            C
0054              CALL ORGPTS(SPMI,SPMA,FDMI,FDMA,3)
            C
            C         PRINT THE INPUT DATA AND RESPONSES
            C
0055              WRITE(6,6002)
0056              DO 6004 J=1,NOBS
0057              WRITE(6,6003)(X(I,J),I=1,NTLCP)
0058        6004  WRITE(6,6005)(Y(K,J),K=1,2)
            C
            C         TABULATE THE RESPONSES
            C
0059              CALL PLOTPM(NOBI)
0060              IF(ICYC.EQ.1)GO TO 12
0061              RETURN
            C
            C         PREPARE THE DATA FOR E V O P
            C
0062        12    DO 14 I=1,4
0063              DO 14 J=1,2
0064              SUM(J,I)=0.0
0065        14    AVE(J,I)=0.0
0066              RETURN
0067        9011  WRITE(6,9027)
0068              GO TO 9033
0069        9012  WRITE(6,9028)
0070              GO TO 9033
0071        9013  WRITE(6,9029)
0072              GO TO 9033
0073        9014  WRITE(6,9030)
0074              GO TO 9033
```

```
0075      9015  WRITE(6,9031)
0076            GO TO 9033
0077      9016  WRITE(6,9032)
0078      9033  CALL EXIT
0079      15    JK=1
0080            IF(TEMP(I,1).NE.SPMI.AND.TEMP(I,1).NE.SPMA)JK=3
0081            IF(TEMP(I,2).NE.FDMI.AND.TEMP(I,2).NE.FDMA)JK=JK+1
0082            GO TO (19,17,18,19),JK
0083      17    WRITE(6,9034)
0084            GO TO 9033
0085      18    WRITE(6,9035)
0086            GO TO 9033
0087      19    WRITE(6,9036)
0088            GO TO 9033
          C
          C         FORMATS
          C
0089      5301  FORMAT(6E13.8/6E13.8/6E13.8/2E13.8,4I2)
0090      5302  FORMAT(8F10.4)
0091      6002  FORMAT('1',T20,31X,'  INPUT VALUES AND COMPUTED RESPONSES '///
               *'0','       SPEED        FEED              PARTS        TIME',T51,20X,
               *'TOOL-EDGES',T105,'       COST   PROD RATE'/' ',T51,
               *                          '  (1)  (2)  (3)  (4)  (5)  (6)  (7)  (8)',
               *'  (9) (10)',T105, '  ($/PIECE) (PIECES/MIN)'
               *               /' ',T51,' (11) (12) (13) (14) (15) (16) (17) (18)',
               *' (19) (20)')
0092      6003  FORMAT('0',F10.0,F10.4,5X,2F10.0,(' ',T51,10F5.0))
0093      6005  FORMAT('+',T105,F10.2,F10.4)
0094      9027  FORMAT('1  ***  ERROR  ***     UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'PUNCHED OUTPUT FROM PREVIOUS EVOP CYCLE MISSING')
0095      9028  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,'IN PUNCH OUTPUT FROM PREVIOUS EVOP CYCLE')
0096      9029  FORMAT('1  ***  ERROR  ***     UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'PUNCHED OUTPUT FROM PREVIOUS REGRESSION STEP MISSING')
0097      9030  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,'IN PUNCH OUTPUT FROM PREVIOUS REGRESSION STEP')
0098      9031  FORMAT('1  ***  ERROR  ***     UNEXPECTED TERMINATION OF DATA ..'
               *,/'0',T19,'NEW OBSERVATIONS MISSING')
0099      9032  FORMAT('1  ***  ERROR  ***   INVALID CHARACTER ENCOUNTERED  '/'0'
               *,T19,'IN NEW OBSERVATIONS -- CHECK YOUR KEYPUNCHING')
0100      9034  FORMAT('0  ***  ERROR  ***   MORE THAN TWO FEED SETTINGS WERE ',
               *'FOUND IN THE NEW OBSERVATIONS ---'/'0',T10,' PROGRAM TERMINATING
               *')
0101      9035  FORMAT('0  ***  ERROR  ***   MORE THAN TWO SPEED SETTINGS WERE ',
               *'FOUND IN THE NEW OBSERVATIONS ---'/'0',T10,' PROGRAM '
               *,'TERMINATING')
0102      9036  FORMAT('0  ***  ERROR  ***   MORE THAN TWO SPEED SETTINGS AND ',
               *'MORE THAN TWO FEED SETTINGS WERE FOUND IN THE NEW OBSERVATIONS',
               *' ---'/'0',T10,' PROGRAM TERMINATING')
0103            END
```

```
0001                SUBROUTINE EVOP
              C
              C
              C          SUBROUTINE EVOP PERFORMS THE EVOLUTIONARY OPERATION ANALYSIS
              C          FOR THE INPUT OBSERVATIONS. THE PROCEDURE USED AND THE RESULTS
              C          REPORTED ARE MODIFICATIONS OF THOSE GIVEN BY BOX AND DRAPER.
              C
              C
0002                COMMON /C101/SPEED(100),FEED(100),SPND(100),NSPD,NFD,ISP,IFD
0003                COMMON /C102/IPH,ICYC,SCYCLE,RLO,X(24,100),Y(2,100),NOBS,NOB1
                   *,IOP,PSP,RFD,NTLC,TLC(20)
0004                COMMON /C103/DIFF(2,4),SUM(2,4),AVE(2,4),SUMS(2),AVES(2,2)
0005                COMMON /C104/F4N(10)
0006                COMMON /C107/IND(4),SMAX,SMIN,FMAX,FMIN
0007                DIMENSION RANGE(2),SEAVES(2),SNAVES(2),SNSUM(2),SNEW(2),SEMEAN(2)
              C
              C          BEGIN PRINTING EVOP TABLE
              C
0008                IEST=1
0009                IF(ICYC.GE.2)IEST=2
0010                WRITE(6,6600)IPH,ICYC
0011                N2=NOB1+1
0012                N3=N2+1
0013                WRITE(6,6553)(X(I,NOB1),X(I,N2),X(I,N3),X(I,NOBS),I=1,2),
                   *(X(2,NOB1),X(2,N2),X(2,N3),X(2,NOBS),I=1,2)
0014                JCYC=SCYCLE
0015                IF(JCYC.LT.2)JCYC=2
0016                IF(JCYC.GT.10)JCYC=10
0017                WRITE(6,6601)((SUM(J,I),I=1,4),J=1,2)
0018                WRITE(6,6602)((AVE(J,I),I=1,4),J=1,2)
0019                SCYCLE=ICYC
              C
              C          COMPUTE THE DIFFERENCES
              C
0020                DO 10 I=1,4
0021                DIFF(1,I)=AVE(1,I)-Y(1,NOB1+I-1)
0022          10    DIFF(2,I)=AVE(2,I)-Y(2,NOB1+I-1)
              C
              C          CALCULATE THE RANGE
              C
0023                DO 120 I=1,2
0024                YMAX=AMAX1(DIFF(I,1),DIFF(I,2),DIFF(I,3),DIFF(I,4))
0025                YMIN=AMIN1(DIFF(I,1),DIFF(I,2),DIFF(I,3),DIFF(I,4))
0026          120   RANGE(I)=YMAX-YMIN
0027                IF(ICYC.LT.2)GO TO 44
              C
              C          CALCULATE NEW S, NEW SUM S, NEW AVERAGE S
              C
0028                DO 466 I=1,2
0029                SNEW(I)=RANGE(I)*F4N(JCYC)
0030                SNSUM(I)=(SNEW(I)    +SUMS(I))
0031                IF(SUMS(I).EQ.0.0)SNSUM(I)=SNEW(I)*2.
0032                SNAVES(I)=     (SNSUM(I))/2.
0033          466   CONTINUE
```

```
0034                GO TO 45
0035          44    DO 467 I=1,2
0036                SNEW(I)=0.0
0037                SNSUM(I)=SUMS(I)
0038          467   SNAVES(I)=AVES(I,1)
              C
              C         CALCULATE 2 STANDARD ERROR ESTIMATES
              C
0039          45    DO 468 I=1,2
0040                SEAVES(I)=2./SQRT(SCYCLE)*SNAVES(I)
0041                SEMEAN(I)=1.73/SQRT(SCYCLE)*SNAVES(I)
0042                IF(SNAVES(I).EQ.AVES(I,1))SNAVES(I)=AVES(I,2)
0043          468   CONTINUE
              C
              C         COMPUTE SUMS AND AVERAGES
              C
0044          47    DO 11 I=1,4
0045                DO 11 J=1,2
0046                SUM(J,I)=SUM(J,I)+Y(J,NOB1+I-1)
0047          11    AVE(J,I)=SUM(J,I)/SCYCLE
              C
              C         FINISH PRINTING THE EVOP TABLE
              C
0048                WRITE(6,6603)((Y(J,I),I=NOB1,NOBS),J=1,2)
0049                WRITE(6,6604)((DIFF(J,I),I=1,4),J=1,2)
0050                WRITE(6,6605)((SUM(J,I),I=1,4),J=1,2)
0051                WRITE(6,6606)((AVE(J,I),I=1,4),J=1,2)
0052                WRITE(6,6620)
              C     WRITE(6,6621)SUMS(1),SUMS(2)
0053                WRITE(6,6622)AVES(1,IEST),AVES(2,IEST)
0054                WRITE(6,6623)SNEW(1),SNEW(2)
0055                WRITE(6,6624)RANGE(1),RANGE(2)
0056                WRITE(6,6625)SNSUM(1),SNSUM(2)
0057                WRITE(6,6626)SNAVES(1),SNAVES(2)
0058                WRITE(6,6607) SEAVES
              C
              C         SAVE COMPUTED VALUES FOR FUTURE CYCLES
              C
0059                WRITE(7,7000)
                   *((SUM(J,I),I=1,4),SNSUM(J),(AVE(J,I),I=1,4),SNAVES(J),J=1,2),
                   *(IND(I),I=1,4)
              C
              C         ANALYZE THE EFFECTS
              C
0060                DO 144 I=1,4
0061          144   AVE(2,I)=-AVE(2,I)
0062                IGO=1
0063                ISP1=ISP
0064                IFD1=IFD
0065          145   GO TO (146,147),IGO
0066          146   WRITE(6,148)
0067                GO TO 149
0068          147   WRITE(6,150)
0069          149   IF(SEAVES(IGO).EQ.0.0)GO TO 999
```

```
      C
      C     CALCULATE THE EFFECTS OF THE VARIABLES
      C
            EFFA=(AVE(IGO,2)+AVE(IGO,3)-AVE(IGO,1)-AVE(IGO,4))/2.
            EFFB=(AVE(IGO,2)+AVE(IGO,4)-AVE(IGO,1)-AVE(IGO,3))/2.
            EFFAB=(AVE(IGO,1)+AVE(IGO,2)-AVE(IGO,3)-AVE(IGO,4))/2.
            IA=0
            IF(ABS(EFFA)-SEAVES(IGO))30,31,31
      C
      C     THE EFFECT OF SPEED IS NOT SIGNIFICANT
      C
      30    WRITE(6,6610)EFFA
            GO TO 32
      C
      C     THE EFFECT OF SPEED IS SIGNIFICANT
      C
      31    IA=IA+1
            WRITE(6,6611)EFFA
      32    IF(ABS(EFFB)-SEAVES(IGO))33,34,34
      C
      C     THE EFFECT OF FEED IS NOT SIGNIFICANT
      C
      33    WRITE(6,6612)EFFB
            GO TO 35
      C
      C     THE EFFECT OF FEED IS SIGNIFICANT
      C
      34    IA=IA+2
            WRITE(6,6613)EFFB
      35    IF(ABS(EFFAB)-SEAVES(IGO))36,37,37
      C
      C     THE EFFECT OF THE INTERACTION IS NOT SIGNIFICANT
      C
      36    WRITE(6,6614)EFFAB
            GO TO 38
      C
      C     THE EFFECT OF THE INTERACTION IS SIGNIFICANT
      C
      37    IA=IA+3
            WRITE(6,6615)EFFAB
      38    IA=IA+1
      C
      C     RECOMMEND THE NEW OPERATING CONDITIONS
      C
      C     THE BASE POINT FOR SHIFTING OPERATIONS IS TAKEN TO BE THE
      C     LOWER LEFT POINT.  ALL OTHER POINTS ARE DETERMINED AS
      C     DISPLACEMENTS FROM THIS POINT.  SHIFTS TO A NEW SET OF
      C     OBSERVATIONS ARE DETERMINED BY SHIFTING THE BASE POINT
      C     AND RECOMPUTING THE OTHER THREE POINTS FROM THE NEW BASE.
      C
            GO TO (999,1001,1002,1012,1013,1023,1123),IA
      C
      C     NONE OF THE EFFECTS ARE SIGNIFICANT
      C
```

```
0091    999   WRITE(6,6617)
0092          GO TO 1000
        C
        C         SPEED IS SIGNIFICANT
        C
0093    1001  IF(EFFA)2000,2001,2001
0094    2000  ISP=ISP+1
        C
        C         DETERMINE IF THE SELECTED POINTS ARE WITHIN THE DEFINED
        C         ENVIRONMENT.
        C
0095    1000  IF(ISP+1-NSPD)2033,2033,2034
0096    2034  ISP=ISP-1
0097          WRITE(6,6018)
0098    2033  IF(IFD+1-NFD)2035,2035,2036
0099    2036  IFD=IFD-1
0100          WRITE(6,6019)
0101    2035  IF(ISP)2037,2037,2038
0102    2037  ISP=ISP+1
0103          WRITE(6,6020)
0104    2038  IF(IFD)2039,2039,2040
0105    2039  IFD=IFD+1
0106          WRITE(6,6021)
0107    2040  WRITE(6,6616)SPEED(ISP),SPEED(ISP+1),FEED (IFD+1),FEED(IFD+1),
             1SPEED(ISP),SPEED(ISP+1),FEED(IFD),FEED(IFD)
        C
        C         PLOT RECOMMENDED OPERATING CONDITIONS
        C
0108          CALL CRDPTS(SPEED(ISP),SPEED(ISP+1),FEED(IFD),FEED(IFD+1),IGO)
0109          ISP=ISP1
0110          IFD=IFD1
0111          IGO=IGO+1
0112          IF(IGO.EQ.2)GO TO 145
0113          RETURN
0114    2001  ISP=ISP-1
0115          GO TO 1000
        C
        C         FEED IS SIGNIFICANT
        C
0116    1002  IF(EFFB)2003,2004,2004
0117    2003  IFD=IFD+1
0118          GO TO 1000
0119    2004  IFD=IFD-1
0120          GO TO 1000
        C
        C         SPEED & FEED OR THE INTERACTION ARE SIGNIFICANT
        C
0121    1012  IF(ABS(EFFA)-SEAVES(IGO))2005,2006,2006
0122    2005  YMIN=AMIN1(Y(IGO,NOB1),Y(IGO,NOB1+1),Y(IGO,NOB1+2),Y(IGO,NOBS))
0123          DO 2007 I=1,4
0124          IF(Y(IGO,NOB1+I-1).EQ.YMIN)GO TO 2008
0125    2007  CONTINUE
0126    2008  GO TO (2009,2010,2011,2012),I
0127    2009  ISP=ISP-1
```

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0128              IFD=IFD-1                                                          EVOP2170
0129              GO TO 1000                                                         EVOP2180
0130       2010   ISP=ISP+1                                                          EVOP2190
0131              IFD=IFD+1                                                          EVOP2200
0132              GO TO 1000                                                         EVOP2210
0133       2011   ISP=ISP+1                                                          EVOP2220
0134              IFD=IFD-1                                                          EVOP2230
0135              GO TO 1000                                                         EVOP2240
0136       2012   ISP=ISP-1                                                          EVOP2250
0137              IFD=IFD+1                                                          EVOP2260
0138              GO TO 1000                                                         EVOP2270
0139       2006   IF(EFFA)2013,2014,2014                                             EVOP2280
0140       2013   ISP=ISP+1                                                          EVOP2290
0141              GO TO 2015                                                         EVOP2300
0142       2014   ISP=ISP-1                                                          EVOP2310
0143       2015   IF(EFFB)2016,2017,2017                                             EVOP2320
0144       2016   IFD=IFD+1                                                          EVOP2330
0145              GO TO 1000                                                         EVOP2340
0146       2017   IFD=IFD-1                                                          EVOP2350
0147              GO TO 1000                                                         EVOP2360
           C                                                                         EVOP2370
           C           SPEED AND THE INTERACTION ARE SIGNIFICANT                     EVOP2380
           C                                                                         EVOP2390
0148       1013   IF(EFFA)2018,2019,2019                                             EVOP2400
0149       2018   ISP=ISP+1                                                          EVOP2410
0150              GO TO 2020                                                         EVOP2420
0151       2019   ISP=ISP-1                                                          EVOP2430
0152              IF(Y(IGC,NOBS)-Y(IGC,NOB1))2021,2021,2022                          EVOP2440
0153       2021   IFD=IFD+1                                                          EVOP2450
0154              GO TO 1000                                                         EVOP2460
0155       2022   IFD=IFD-1                                                          EVOP2470
0156              GO TO 1000                                                         EVOP2480
0157       2020   IF(Y(IGC,NOB1+1)-Y(IGC,NOB1+2))2021,2022,2022                      EVOP2490
           C                                                                         EVOP2500
           C           FEED AND THE INTERACTION ARE SIGNIFICANT                      EVOP2510
           C                                                                         EVOP2520
0158       1023   IF(EFFB)2023,2024,2024                                             EVOP2530
0159       2023   IFD=IFD+1                                                          EVOP2540
0160              GO TO 2025                                                         EVOP2550
0161       2024   IFD=IFD-1                                                          EVOP2560
0162              IF(Y(IGC,NOB1+2)-Y(IGC,NOB1))2027,2026,2026                        EVOP2570
0163       2026   ISP=ISP-1                                                          EVOP2580
0164              GO TO 1000                                                         EVOP2590
0165       2027   ISP=ISP+1                                                          EVOP2600
0166              GO TO 1000                                                         EVOP2610
0167       2025   IF(Y(IGC,NOB1+1)-Y(IGC,NOBS))2027,2026,2026                        EVOP2620
           C                                                                         EVOP2630
           C           ALL TERMS ARE SIGNIFICANT                                     EVOP2640
           C                                                                         EVOP2650
0168       1123   IF(EFFA)2028,2029,2029                                             EVOP2660
0169       2028   ISP=ISP+1                                                          EVOP2670
0170              GO TO 2030                                                         EVOP2680
0171       2029   ISP=ISP-1                                                          EVOP2690
0172       2030   IF(EFFB)2031,2032,2032                                             EVOP2700
```

```
0173        2031  IFD=IFD+1
0174              GO TO 1000
0175        2032  IFD=IFD-1
0176              GO TO 1000
            C
            C          FORMATS
            C
0177        148   FORMAT('1',T46,'COST ANALYSIS')
0178        150   FORMAT('1',T46,'PRODUCTION RATE ANALYSIS')
0179        6018  FORMAT('0THE RECOMMENDED SPEED HAS EXCEEDED THE MAXIMUN DEFINED ',
                 1'SPEED LIMIT'/'0',10X,'THE PREVIOUS SETTINGS SHOULD BE RE-EXAMIN',
                 2'ED')
0180        6019  FORMAT('0THE RECOMMENDED  FEED HAS EXCEEDED THE MAXIMUN DEFINED ',
                 1 'FEED LIMIT'/'0',10X,'THE PREVIOUS SETTINGS SHOULD BE RE-EXAMIN',
                 2'ED')
0181        6020  FORMAT('0THE RECOMMENDED SPEED HAS FALLEN BELOW THE MINIMUM ',
                 *'DEFINED ',
                 1'SPEED LIMIT'/'0',10X,'THE PREVIOUS SETTINGS SHOULD BE RE-EXAMIN',
                 2'ED')
0182        6021  FORMAT('0THE RECOMMENDED  FEED HAS FALLEN BELOW THE MINIMUM ',
                 *'DEFINED ',
                 1 'FEED LIMIT'/'0',10X,'THE PREVIOUS SETTINGS SHOULD BE RE-EXAMIN',
                 2'ED')
0183        6553  FORMAT('0',T10,'SPEED (RPM)', T25,4F10.0,10X,4F10.0/'0',T10,'FEED'
                 *,' (IPR)',T25,4F10.4,10X,4F10.4)
0184        6600  FORMAT('1',T42,'EVOLUTIONARY OPERATION ANALYSIS',/T47,
                 *'PHASE ',I3,
                 1'  CYCLE ',I3//'0',T46,'CALCULATION OF AVERAGES '/'0',T45,'COST',
                 2T90,'PRODUCTION RATE'/          '0OPERATING CONDITIONS')
0185        6601  FORMAT(/'0PREVIOUS CYCLE SUM',T25,4F10.2,10X,4F10.4)
0186        6602  FORMAT('0PREVIOUS CYCLE AVERAGE',T25,4F10.2,10X,4F10.4)
0187        6603  FORMAT('0NEW OBSERVATIONS',T25,4F10.2,10X,4F10.4)
0188        6604  FORMAT('0DIFFERENCES',T25,4F10.2,10X,4F10.4)
0189        6605  FORMAT('0NEW SUMS',T25,4F10.2,10X,4F10.4)
0190        6606  FORMAT('0NEW AVERAGES: Y(I)',T25,4F10.2,10X,4F10.4)
0191        6607  FORMAT(//'0',T46,'CALCULATION OF 2 S.E. LIMITS:'//'0',
                 *'FOR NEW EFFECTS',T35,F10.4,T85,F10.4)
0192        6610  FORMAT('0THE EFFECT OF SPEED IS ',T53,F10.4,'  --- NOT ',
                 *'SIGNIFICANT ---')
0193        6611  FORMAT('0THE EFFECT OF SPEED IS ',T88,F10.4,'  *** -- SIGNIFICANT'
                 *,' -- ***')
0194        6612  FORMAT('0THE EFFECT OF FEED IS ',T53,F10.4,'  --- NOT SIGNIFICANT'
                 *,' ---')
0195        6613  FORMAT('0THE EFFECT OF FEED IS ',T88,F10.4,'  *** -- SIGNIFICANT'
                 *,' -- ***')
0196        6614  FORMAT('0THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS ',
                 1F10.4,'  --- NOT SIGNIFICANT ---')
0197        6615  FORMAT('0THE EFFECT OF THE INTERACTION OF SPEED AND FEED IS',T88,
                 1F10.4,'  *** -- SIGNIFICANT -- ***')
0198        6616  FORMAT(///'0',T15,'RECOMMEND ADDITIONAL OBSERVATIONS BE TAKEN AT '
                 1,'POINTS:'///' ',T15,'4) SPEED = ',F10.0,T45,'2) SPEED = ',F10.0/
                 1' ',T15,'   FEED = ',F10.4,T45,'   FEED = ',F10.4////'0',
                 1T15,'1) SPEED = ',F10.0,T45,'3) SPEED = ',F10.0/' ',
                 1' ',T15,'   FEED = ',F10.4,T45,'   FEED = ',F10.4)
```

```
0199        6617  FORMAT('0NO PARAMETERS ARE SIGNIFICANT'/'0','THE PREVIOUS SETTING'EVOP3250
                 1,'S SHOULD BE RE-EXAMINED')                                     EVOP3260
0200        6620  FORMAT(//'0',T44,'CALCULATION OF STANDARD DEVIATIONS'//)         EVOP3270
                 C 6621  FORMAT('0','PREVIOUS SUM S',T35,F10.4,T85,F10.4)         EVOP3280
0201        6622  FORMAT('0PREVIOUS AVERAGE S',T35,F10.4,T85,F10.4)               EVOP3290
0202        6623  FORMAT('0NEW S = RANGE * F4,N',T35,F10.4,T85,F10.4)             EVOP3300
0203        6624  FORMAT('0RANGE',T35,F10.4,T85,F10.4)                            EVOP3310
0204        6625  FORMAT('0NEW SUM S',T35,F10.4,T85,F10.4)                        EVOP3320
0205        6626  FORMAT('0NEW AVERAGE S = NEW SUM S/2     ',T35,F10.4,T85,F10.4) EVOP3330
0206        7000  FORMAT('0.12345'/6E13.8/6E13.8/6E13.8/2E13.8,4I2)               EVOP3340
0207              END                                                             EVOP3350
```

```
0001              SUBROUTINE ORGPTS(SP1,SP2,FD1,FD2,IGO)                          ORGP  10
            C                                                                     ORGP  20
            C      SUBROUTINE ORGPTS PLOTS EACH DEFINED FEED-SPEED COMBINATION    ORGP  30
            C      AS A '.' ON A GRAPH AND INDICATES THE FOUR POINTS OF PARTICULAR ORGP  40
            C      INTEREST WITH AN '*'                                           ORGP  50
            C                                                                     ORGP  60
0002              COMMON /C101/SPEED(100),FEED(100),SPND(100),NSPD,NFD,ISP,IFD    ORGP  70
0003              COMMON /C105/PT1,PT2,PT3,NAME(50),CHART(100,50)                 ORGP  80
0004              DIMENSION FND(50)                                               ORGP  90
0005              DO 6 I=1,50                                                     ORGP 100
0006        6     FND(I)=0.0                                                      ORGP 110
0007              NS=100/NSPD                                                     ORGP 120
0008              NF=50/NFD                                                       ORGP 130
0009              NS1=NS*NSPD                                                     ORGP 140
0010              NF1=NF*NFD                                                      ORGP 150
0011              ISP1=1                                                          ORGP 160
0012              ISP2=1                                                          ORGP 170
0013              NFD1=1                                                          ORGP 180
0014              NFD2=1                                                          ORGP 190
0015              DO 1 IS=1,NSPD                                                  ORGP 200
0016              IF(SP1.EQ.SPEED(IS))ISP1=(IS-1)*NS+1                            ORGP 210
0017              IF(SP2.EQ.SPEED(IS))ISP2=(IS-1)*NS+1                            ORGP 220
0018        1     CONTINUE                                                        ORGP 230
0019              DO 2 JS=1,NFD                                                   ORGP 240
0020              IF(FD1.EQ.FEED(JS))NFD1=(JS-1)*NF+1                             ORGP 250
0021              IF(FD2.EQ.FEED(JS))NFD2=(JS-1)*NF+1                             ORGP 260
0022        2     CONTINUE                                                        ORGP 270
0023              K=0                                                             ORGP 280
0024              DO 3 I=1,NF1,NF                                                 ORGP 290
0025              K=K+1                                                           ORGP 300
0026        3     FND(I)=FEED(K)                                                  ORGP 310
            C     DO 3 J=1,NS1,NS                                                 ORGP 320
            C 3   CHART(J,I)=PT1                                                  ORGP 330
0027              CHART(ISP1,NFD1)=PT2                                            ORGP 340
0028              CHART(ISP1,NFD2)=PT2                                            ORGP 350
0029              CHART(ISP2,NFD1)=PT2                                            ORGP 360
0030              CHART(ISP2,NFD2)=PT2                                            ORGP 370
0031              GO TO (31,32,33),IGO                                            ORGP 380
0032        31    WRITE(6,64)                                                     ORGP 390
0033              GO TO 34                                                        ORGP 400
0034        32    WRITE(6,65)                                                     ORGP 410
0035              GO TO 34                                                        ORGP 420
0036        33    WRITE(6,66)                                                     ORGP 430
0037        34    I=50                                                            ORGP 440
0038        4     IF(FND(I).EQ.0.0)GO TO 5                                        ORGP 450
0039              WRITE(6,67)NAME(I),FND (I),(CHART(J,I),J=1,100)                 ORGP 460
0040              GO TO 8                                                         ORGP 470
0041        5     WRITE(6,69)NAME(I),(CHART(J,I),J=1,100)                         ORGP 480
0042        8     I=I-1                                                           ORGP 490
0043              IF(I.GT.0)GO TO 4                                               ORGP 500
0044              K=0                                                             ORGP 510
0045              DO 11 I=1,10                                                    ORGP 520
0046              DO 11 J=I,NSPD,10                                               ORGP 530
0047              K=K+1                                                           ORGP 540
```

```
0048     11     SPND(J)=SPEED(K)                                              ORGP 550
0049            WRITE(6,70)                                                   ORGP 560
0050            WRITE(6,71)(SPND(I),I=1,NSPD)                                 ORGP 570
0051            WRITE(6,72)                                                   ORGP 580
0052            CHART(ISP1,NFD1)=PT3                                          ORGP 590
0053            CHART(ISP1,NFD2)=PT3                                          ORGP 600
0054            CHART(ISP2,NFD1)=PT3                                          ORGP 610
0055            CHART(ISP2,NFD2)=PT3                                          ORGP 620
0056            RETURN                                                        ORGP 630
         C                                                                    ORGP 640
         C          FORMATS                                                   ORGP 650
         C                                                                    ORGP 660
0057     64     FORMAT('1',T54,'NEW COST ENVIRONMENT')                        ORGP 670
0058     65     FORMAT('1',T54,'NEW PRODUCTION RATE ENVIRONMENT')             ORGP 680
0059     66     FORMAT('1',T54,'SPECIFIED ENVIRONMENT'/' ')                   ORGP 690
0060     67     FORMAT(' ',1A1,F10.4,2X,'I',2X,100A1)                         ORGP 700
0061     69     FORMAT(' ',1A1,12X,'I',2X,100A1)                              ORGP 710
0062     70     FORMAT(' ',13X,'I'/                                           ORGP 720
               *       ' ',13X,'I-------------------------------------------------', ORGP 730
               *'-----------------------------------------------------')     ORGP 740
0063     71     FORMAT(' ',7X,10F10.0)                                        ORGP 750
0064     72     FORMAT(' ',T60,'S P E E D  (RPM)')                            ORGP 760
0065            END                                                           ORGP 770
```

```
0001                SUBROUTINE PLOTPM(I1)
              C
              C         SUBROUTINE PLOTPM TABULATES THE RESPONSES VERSUS FEEDS
              C         AND SPEEDS.
              C
0002                COMMON /C102/IPH,ICYC,SCYCLE,RLD,X(24,100),Y(2,100),NOBS,NUBI
                   *,IUP,BSP,BFD,NILC,TLC(20)
0003                I2=I1+1
0004                I3=I1+2
0005                I4=I1+3
0006                WRITE(6,72)
0007                WRITE(6,71)X(2,I4),Y(1,I4),Y(1,I2),Y(2,I4),Y(2,I2),X(2,I1),
                   *Y(1,I1),Y(1,I3),Y(2,I1),Y(2,I3),X(1,I1),X(1,I3)
0008                RETURN
              C
              C         FORMATS
              C
0009          71    FORMAT('0',30X,F10.4,'  COST       = ',F10.2,10X,'  COST       = ',
                   *F10.2
                   */'0',40X,'  PROD. RT. = ',F10.4,10X,'  PROD. RT. = ',F10.4////
                   *'0',30X,F10.4,'  COST       = ',F10.2,10X,'  COST       = ',F10.2
                   */'0',40X,'  PROD. RT. = ',F10.4,10X,'  PROD. RT. = ',F10.4/
                   *'0',54X,F10.0,24X,F10.0/'0',69X,'S P E E D (RPM)')
0010          72    FORMAT('1',30X,'  TABLE OF RESPONSES '///'0',33X,'  FEED (IPR)')
0011                END
```

```
      SUBROUTINE REGPLT(BC,B,IND,IREG,IGO)
C
C         SUBROUTINE REGPLT PREDICTS THE PERFORMANCE INDICIES FOR
C         FEEDS AND SPEEDS ADJACENT TO THE OBSERVATIONS.
C
      COMMON /C101/SPEED(100),FEED(100),SPNC(100),NSPD,NFD,ISP,IFD
      DIMENSION IND(4),B(2,5),SPDD(2,100),BO(2),IREG(2)
      DATA PTT1,PTT2/'(',')'/
      WRITE(6,71)
C
C         COMPUTE PREDICTED VALUES
C
   81 ISP1=IND(1)-1
      IF(ISP1.LE.0)ISP1=1
      ISP2=IND(2)+1
      IF(ISP2.GT.NSPD)ISP2=NSPD
      IFD1=IND(3)-1
      IF(IFD1.LE.0)IFD1=1
      IFD2=IND(4)+1
      IF(IFD2.GT.NFD)IFD2=NFD
      I=IFD2
  505 C=ALOG(FEED(I))
      DO 506 J=ISP1,ISP2
      A=ALOG(SPEED(J))
      DO 506 K=1,2
      IRE=IREG(K)
      SPDD(K,J) = BO(K) +B(K,1) *A + B(K,2)*C
      GO TO (506,511,512,513,514), IRE
  511 SPDD(K,J) = SPDD(K,J) + B(K,3)*A*C + B(K,4)*A*A
      GO TO 506
  512 SPDD(K,J) = SPDD(K,J) + B(K,3)*A*C + B(K,4)*C*C
      GO TO 506
  513 SPDD(K,J) = SPDD(K,J) + B(K,3)*A*C + B(K,4)*A*A + B(K,5)*C*C
      GO TO 506
  514 SPDD(K,J) = SPDD(K,J) + B(K,3)*A*C
  506 CONTINUE
C
C         PLOT PREDICTED VALUES
C
      ID=ISP2-ISP1+1
      IF(ID.GT.10)GO TO 11
      WRITE(6,72)FEED(I),(SPDD(1,J),J=ISP1,ISP2)
      WRITE(6,78)(PTT1,SPDD(2,J),PTT2,J=ISP1,ISP2)
      GO TO 77
   11 IST=ISP1
   33 IEND=IST+9
      IEND=MIN0(IEND,ISP2)
      IF(IST.EQ.ISP1)WRITE(6,72)FEED(I),(SPDD(1,J),J=IST,IEND)
      IF(IST.NE.ISP1)WRITE(6,82)        (SPDD(1,J),J=IST,IEND)
      WRITE(6,78)(PTT1,SPDD(2,J),PTT2,J=IST,IEND)
      IF(IST.GE.ISP2)GO TO 77
      IST=IST+10
      GO TO 33
   77 I=I-1
```

```
0045              IF(I.GE.IFDI)GO TC 505
0046              WRITE(6,70)
0047              WRITE(6,73)(SPEED(I),I=ISP1,ISP2)
0048              IF(ID.GT.5)GO TC 98
0049              WRITE(6,74)
0050        99    CALL EXIT
0051        98    WRITE(6,75)
0052              GO TO 99
            C
            C         FORMATS
            C
            C
0053        70    FORMAT(' ',12X,'I '/
                 *        ' ',12X,'I--------------------------------------------------',
                 *'----------------------------------------------------------')
0054        71    FORMAT('1',T50,'PRECICTED COSTS '/' ',T44,'(PREDICTED PRODUCTION'
                 *,' RATES)'//'0     FEED (IPR)'/'0')
0055        72    FORMAT(' ',12X,'I'/' ',F10.4,2X,'I',2X,10F10.2)
0056        73    FORMAT('0',15X,10F10.0)
0057        74    FORMAT('0',T30,'S P E E D  (RPM)')
0058        75    FORMAT('0',T50,'S P E E D  (RPM)')
0059        78    FORMAT(          ' ',12X,'I',3X,10(2X,A1 ,F6.4,A1 ))
0060        82    FORMAT(' ',12X,'I'/' ',12X,'I',2X,10F10.2)
0061              END
```

```
0001            SUBROUTINE REGRES (X,Y,N,IREG,BSUBO,BHAT,IDEP)
          C
          C          SUBROUTINE REGRES COMPUTES A MULTIPLE LINEAR REGRESSION ON
          C          M VARIABLES WITH N OBSERVATIONS.  EQUATIONS USED ARE:
          C
          C          PI = BC + B1 LN(SPEED) + B2 LN(FEED)
          C
          C          PI = B0 + B1 LN(SPEED) + B2 LN(FEED) + B3 LN(SPEEC) LN(FEED)
          C
          C          PI = B0 + B1 LN(SPEED) + B2 LN(FEED) + B3 LN(SPEEC) LN(FEED)
          C                   + B4 LN(SPEED)**2
          C
          C          PI = B0 + B1 LN(SPEED) + B2 LN(FEED) + B3 LN(SPEEC) LN(FEED)
          C                   + B4 LN(FEED)**2
          C
          C          PI = B0 + B1 LN(SPEED) + B2 LN(FEED) + B3 LN(SPEEC) LN(FEED)
          C                   + B4 LN(SPEED)**2 + B5 LN(FEED)**2
          C
          C
0002            DIMENSION BHAT(5),YBAR(2)
0003            DIMENSION X(24,100),Y(2,100),DUM1(5,5),XPX(5,6)
0004            DIMENSION XBAR(5),             RAD(5),STD(5),T(5),YHAT(100),
               *DIFF(100),         XPY(2,5),SST(2)
0005            DIMENSION XPXC(5,6),XPYC(2,5)
0006            NP = N
0007            EPS = 1.0E-05
0008      50    M = 5
0009            XN = N
0010            MP = M+1
0011            IF(IDEP.EQ.1)GO TO 30
0012            DO 10 I=1,5
0013            DO 10 J=1,5
0014      10    XPX(I,J)=DUM1(I,J)
0015            DO 11 I=1,5
0016      11    XPX(I,6)=XPY(2,I)
0017            GO TO 136
          C
          C          COMPUTE THE MEANS
          C
0018      30    DO 40 J = 1,NP
0019            X(1,J) = ALOG(X(1,J))
0020            X(2,J) = ALOG(X(2,J))
0021            X(3,J) = X(1,J)*X(2,J)
0022            X(4,J) = X(1,J)*X(1,J)
0023            X(5,J) = X(2,J)*X(2,J)
0024      40    CONTINUE
0025            DO 60 J=1,2
0026            YBAR(J    )=0.0
0027            DO 60 I=1,N
0028      60    YBAR(J    )=YBAR(J    )+Y(J    ,I)/XN
0029            DO 30 J=1,M
0030            XBAR(J) = 0.0
0031            DO 70 I=1,N
0032      70    XBAR (J)=XBAR(J)+X(J,I)/XN
```

```
0033      80    CONTINUE
          C
          C          COMPUTE THE SUMS OF SQUARES
          C
0034            DO 90 I=1,2
0035            SST(I)=0.0
0036            DO 90 J=1,N
0037      90    SST(I)=SST(I)+(Y(I,J)-YBAR(I))*(Y(I,J)-YBAR(I))
0038            DO 110 J=1,M
0039            DO 110 I=1,M
0040            XPX(J,I) = 0.0
0041            DO 100 K=1,N
0042      100   XPX(J,I)=XPX(J,I)+(X(I,K)-XBAR(I))*(X(J,K)-XBAR(J))
0043            XPXC(J,I)=XPX(J,I)
0044      110   CONTINUE
0045            DO 130 K=1,2
0046            DO 130 J=1,M
0047            XPY(K    ,J) = 0.0
0048            DO 120 I=1,N
0049      120   XPY(K    ,J)=XPY(K    ,J)+(X(J,I)-XBAR(J))*(Y(K    ,I)-YBAR(K    ))
0050            XPYC(K,J)=XPY(K,J)
0051      130   CONTINUE
0052            DO 140 I=1,M
0053      140   XPX(I,6   )=XPY(IDEP,I)
0054            DO 135 I=1,5
0055            DO 135 J=1,5
0056            DUM1(I,J) = XPX(I,J)
0057      135   CONTINUE
          C
          C          DETERMINE THE FORM OF THE REGRESSION EQUATION AND
          C          INVERT THE X'X MATRIX
          C
0058      136   GO TO (151,143,142,146), IREG
0059      142   DO 144 I=1,3
0060            XPX(4,I)=XPX(5,I)
0061      144   XPX(I,4)=XPX(I,5)
0062            XPX(4,4)=XPX(5,5)
0063      143   M=4
0064            DO 141 I = 1,M
0065      141   XPX(I,5) = XPX(I,6)
0066            CALL CIMEQN(XPX,M,EPS,D,1)
0067            IF (ABS(D) .GE. EPS) GO TO 145
0068            GO TO 143
0069      151   M = 2
0070            XPX (1,3) = XPX(1,6)
0071            XPX(2,3) = XPX(2,6)
0072            GO TO 154
0073      146   CALL CIMEQN(XPX,M,EPS,D,1)
0074            IF (ABS(D)) .GE. EPS) GO TO 145
0075      148   IREG = 5
0076            DO 149 I=1,3
0077            DO 149 J=1,3
0078      149   XPX(I,J)=DUM1(I,J)
0079            M = 3
```

```
0080          DO 147 I=1,3                                                REGR1090
0081     147  XPX(I,4)=XPX(I,6)                                           REGR1100
0082     154  CALL DIMECN(XPX,M,EPS,D,1)                                  REGR1110
         C                                                                REGR1120
         C        COMPUTE THE REGRESSION PARAMETERS                       REGR1130
         C                                                                REGR1140
0083     145  DO 150 I = 1,M                                              REGR1150
0084     150  BHAT (I)=XPX(I,M+1)                                         REGR1160
0085          W = 0.0                                                     REGR1170
0086          SSR = 0.0                                                   REGR1180
0087          DO 160 I=1,M                                                REGR1190
0088          W = W + BHAT(I)*XBAR(I)                                     REGR1200
0089          BSUBO = YBAR(IDEP) - W                                      REGR1210
0090     160  SSR=SSR + BHAT(I) * XPY (IDEP,I)                            REGR1220
0091          XM = M                                                      REGR1230
0092          XMSR = SSR/XM                                               REGR1240
0093          SSE = SST(IDEP) - SSR                                       REGR1250
0094          XE = N-M-1                                                  REGR1260
0095          K = XE                                                      REGR1270
0096          XMSE = SSE/XE                                               REGR1280
0097          F = XMSR/XMSE                                               REGR1290
0098          DO 170 I=1,M                                                REGR1300
0099          RAD(I) = XPX(I,I)*XMSE                                      REGR1310
0100          STD(I)=SQRT(RAD(I))                                         REGR1320
0101          T(I) = BHAT(I)/STD(I)                                       REGR1330
0102     170  CONTINUE                                                    REGR1340
0103          DO 190 I=1,N                                                REGR1350
0104          YHAT(I) = BSUBO                                             REGR1360
0105          DO 180 J=1,M                                                REGR1370
0106     180  YHAT (I)=YHAT(I)+BHAT(J)*X(J,I)                             REGR1380
0107          DIFF(I) = Y(IDEP,I)- YHAT(I)                                REGR1390
0108     190  CONTINUE                                                    REGR1400
0109          WRITE (6,503) M,N                                           REGR1410
         C                                                                REGR1420
         C        OUTPUT THE REGRESSION RESULTS                           REGR1430
         C                                                                REGR1440
         C                                                                REGR1450
         C                                            -1                  REGR1460
         C        IF OUTPUT OF THE X'X, X'Y, (X'X)   & RESIDUALS IS DESIRED,  REGR1470
         C        THE FOLLOWING COMMENT CARDS SHOULD BE ACTIVATED BY      REGR1480
         C        REMOVING THE C'S                                        REGR1490
         C                                                                REGR1500
0110          GO TO (521,522),IDEP                                        REGR1510
0111     521  WRITE(6,523)                                                REGR1520
0112          GO TO 525                                                   REGR1530
0113     522  WRITE(6,524)                                                REGR1540
0114     525  RSQ = SSR/SST(IDEP)                                         REGR1550
         C    WRITE (6,505)                                               REGR1560
         C    DO 200 I=1,M                                                REGR1570
         C200 WRITE (6,506) I,(XPXC(I,J),J=1,M)                           REGR1580
         C    WRITE (6,515)                                               REGR1590
         C    DO 210 I=1,M                                                REGR1600
         C210 WRITE (6,516) I,XPYC(IDEP,I)                                REGR1610
         C    WRITE (6,507)                                               REGR1620
```

```
             C      DO 220 I=1,M
             C220   WRITE (6,508) I,(XPX(I,J),J=1,M)
0115                N1 = N - 1
0116                WRITE(6,509) N1,SST(IDEP),M,SSR,XMSR,F,K,SSE,XMSE,RSQ
0117                WRITE (6,510) BSUBC
0118                DO 230 I=1,M
0119         230    WRITE (6,511) I,BHAT (I),I,T(I) ,I,STD(I)
             C      WRITE (6,512)
             C      DO 240 I=1,N
             C240   WRITE (6,513)I,Y(IDEP,I),YHAT (I),DIFF(I)
0120                RETURN
             C
             C          FORMATS
             C
0121         503    FORMAT (1H1,26X, 22HMULTIPLE REGRESSION ON, I3, 15H VARIABLES WITH
                   $I5, 13H OBSERVATIONS ///)
             C504   FORMAT (1H ,1X,4HROW,I3,3X,6E18.8/(12X,6E18.8))
             C505   FORMAT(1H0,10X,'CORRECTED X''X MATRIX'///)
             C506   FORMAT (1H ,1X,4HROW,I3,3X,6E18.8/(12X,6E18.8))
             C507   FORMAT( /////11X,'CORRECTED X''X INVERSE MATRIX' ///)
             C508   FORMAT (1H ,1X,4HROW,I3,3X,6E18.8/(12X,6E18.8))
0122         509    FORMAT (1H0,/,44X,5HANOVA///11X,6HSOURCE,8X,2HDF,10X,2HSS,
                   *10X,2HMS,10X,1HF,17X///11X,5HTOTAL,9X,I3,2X,E18.8//11X,
                   *10HREGRESSION,4X,I3,2X,3E18.8,//11X,8HRESIDUAL,6X,I3,2X,
                   *2E18.8///// 11X,'COEFFICIENT OF MULTIPLE DETERMINATION (R**2) = '
                   *,E13.8///)
0123         510    FORMAT(22X,12HCOEFFICIENTS,15X,8HT VALUES,20X13HSTANDARD DEV.//11X
                   * 9HBSUB0    = ,E15.8)
0124         511    FORMAT(11X,5HBHAT(,I2,2H)=,E15.9,10X,2HT(,I2,2H)=,F15.8,10X,3HSD(,
                   *I2,2H)=,E15.8)
             C512   FORMAT (1H1,10X,'OBSERVATION',12X,'Y-OBSERVED',10X,'Y-ESTIMATED'
             C      *      ,9X, ' DIFFERENCE ' , /////////)
             C513   FORMAT (1H ,10X,I3,19X,E15.8,5X,E15.8,5X,E15.8)
             C514   FORMAT (I2,2X,I3,2X,I3)
             C515   FORMAT (    ////////////////,11X,20HCORRECTED X'Y MATRIX////)
             C516   FORMAT (   2X,4HROW ,I3,3X,6E18.8/(11X,6E18.8))
0125         523    FORMAT('0',T50,'COST EQUATION')
0126         524    FORMAT('0',T50,'PRODUCTION RATE EQUATION')
0127                END
```

```
      SUBROUTINE DIMEQN(A,N,EPS,DET,NSOLUT)
C
C     SUBROUTINE DIMEQN IS A SINGLE PRECISION MATRIX INVERSION ROUTINE
C     THAT SEEKS MAXIMUM PIVIT ELEMENTS AND INVERTS IN PLACE.
C          A= ARRAY CONTAINING MATRIX OF COEFFICIENTS TO BE INVERTED.
C          N= ORDER OF MATRIX A.
C        ESP= MINIMUM ALLOWABLE VALUE OF MATRIX PIVIT BEFORE MATRIX IS
C             TERMED SINGULAR.
C        DET= VALUE OF DETERMINANT OF MATRIX A.
C     NSOLUT= NO. SOLUTION VECTORS IN THE AUGMENTED MATRIX.
C
      DIMENSION IPIV(2, 20),ICJ (20),Y( 20),A(5,6)
         IF(N.LT.1)RETURN
         IF(N.GT. 1)GO TO 250
          DET=A(1,1)
         A(1,1)=1./A(1,1)
         A(1,2)=A (1,1)*A(1,2)
         RETURN
  250  CONTINUE
      M = N + NSOLUT
      DET = 1.0
      ASSIGN 205 TO IZERO
      DO 100 K=1,N
      KM1 = K-1
      IF(KM1.GT.0) ASSIGN 95 TO IZERO
      BIGA = 0.0
      DO 101 I=1,N
      DO 101 J=1,N
      GO TO IZERO ,(95,205)
   95 DO 102 II=1,KM1
      IF(I.EQ.IPIV(1,II).OR.J.EQ.IPIV(2,II)) GO TO 101
  102 CONTINUE
  205 CONTINUE
      IF ( ABS(A(I,J)).LT.BIGA) GO TO 101
      BIGA = ABS(A(I,J))
      IPIV(1,K) = I
      IPIV(2,K) = J
  101 CONTINUE
      IF(BIGA.GE.EPS) GO TO 201
      DET = 0.0
      GO TO 200
  201 IR = IPIV(1,K)
      JC = IPIV(2,K)
      BIGA = A(IR,JC)
      DET = DET*BIGA
      DO 103 LL= 1,M
  103 A(IR,LL) = A(IR,LL)/BIGA
      A(IR,JC) = 1.0/BIGA
      DO 100 LLL= 1,N
      AJCK = A(LLL,JC)
      IF(LLL.EQ.IR) GO TO 100
      A(LLL,JC) = -AJCK/BIGA
      DO 104 L4 = 1,M
      IF(L4.EQ.JC) GO TO 104
```

```
          A(LLL,L4) = A(LLL,L4) -AJCK*A(IR,L4)
     104  CONTINUE
     100  CONTINUE
          DO 105 I=1,N
          IR = IPIV(1,I)
          ICJ(IR) = JC
     105  CONTINUE
          ICT = 0
          NM1 = N-1
          DO 106 I=1,NM1
          IP1 = I + 1
          DO 106 J= IP1,N
          IF(ICJ(J).GE.ICJ(I)) GO TO 106
          ITEMP = ICJ(J)
          ICJ(J) = ICJ(I)
          ICJ(I) = ITEMP
          ICT = ICT + 1
     106  CONTINUE
          IF((ICT/2)*2.NE.ICT) DET = -DET
          DO 107 J=1,M
          DO 108 I=1,N
          JC = IPIV(2,I)
          IR = IPIV(1,I)
     108  Y(JC) = A(IR,J)
          DO 107 K= 1,N
     107  A(K,J) = Y(K)
          DO 110 I= 1,N
          DO 111 J= 1,N
          IR = IPIV(1,J)
          JC = IPIV(2,J)
     111  Y(IR) = A(I,JC)
          DO 110 K = 1,N
     110  A(I,K) = Y(K)
     200  RETURN
          END
```

```
FORTRAN IV G LEVEL  21                BLK DATA            DATE = 73361          15/21/16

0001              BLOCK DATA
            C
            C     DEFINITION  OF  CONSTANTS
            C
0002              COMMON /C104/F4N(10)
0003              COMMON /C105/PT1,PT2,PT3,NAME(50),CHART(100,50)
0004              COMMON /C107/IND(4),SMAX,SMIN,FMAX,FMIN
0005              DATA F4N/0.,.34,.40,.42,.43,.44,.45,.45,.46,.46/
0006              DATA PT1,PT2,PT3/'.','*',' '/
0007              DATA NAME/50*' '/
0008              DATA NAME(16),NAME(17),NAME(18),NAME(19),NAME(20)/'-','R','P',
                 *'I','-'/
0009              DATA NAME(22),NAME(24),NAME(26),NAME(28)/'D','E','E','F'/
0010              DATA CHART/5000*' '/
0011              DATA IND/100,0,100,0/
0012              DATA SMAX,SMIN,FMAX,FMIN/0.0,0.0,0.0,0.0/
0013              END
```

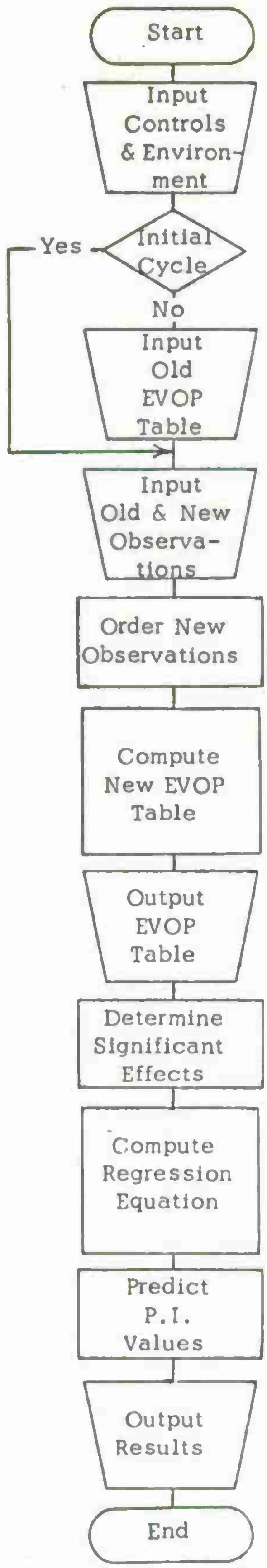
Appendix G. MACHOP Program Documentation

G.1 Program Description

G.1.1 Synopsis

The MACHOP program is written in FORTRAN IV for an IBM System 360/65 Data Processing System using the standard IBM FORTRAN(G) compiler. The following documentation outlines all aspects of this application unique to this program.

G.1.2 MACHOP BLOCK DIAGRAM



G.1.3 Program Sequence

MACHOP consists of one main routine and eight subroutines. The normal sequence is:

MAIN
NUCYCL
EVOP
ORGPTS
PLOTPM
REGPLT
REGRES
DIMEQN
BLOCK DATA

Functions which are required, but are not supplied with this program, are available in most IBM FORTRAN IV compilers. These are as follows:

Square Root (SQRT)
Absolute Value (ABS)
Maximum (AMAX1)
Minimum (AMIN1)
Natural Logarithm (ALOG)

G.1.4 Program Requirements and Restrictions

The MACHOP routine uses a building block approach to examine the response surface. The output from a cycle must be included in the input for the next cycle in order to evaluate correctly the new observations. If at any point in this process, output from the previous cycle is omitted from the input of a subsequent cycle, the results will be invalid.

The following restrictions apply to the MACHOP program:

1. The number of speeds defined for this operation must be less than or equal to 100.

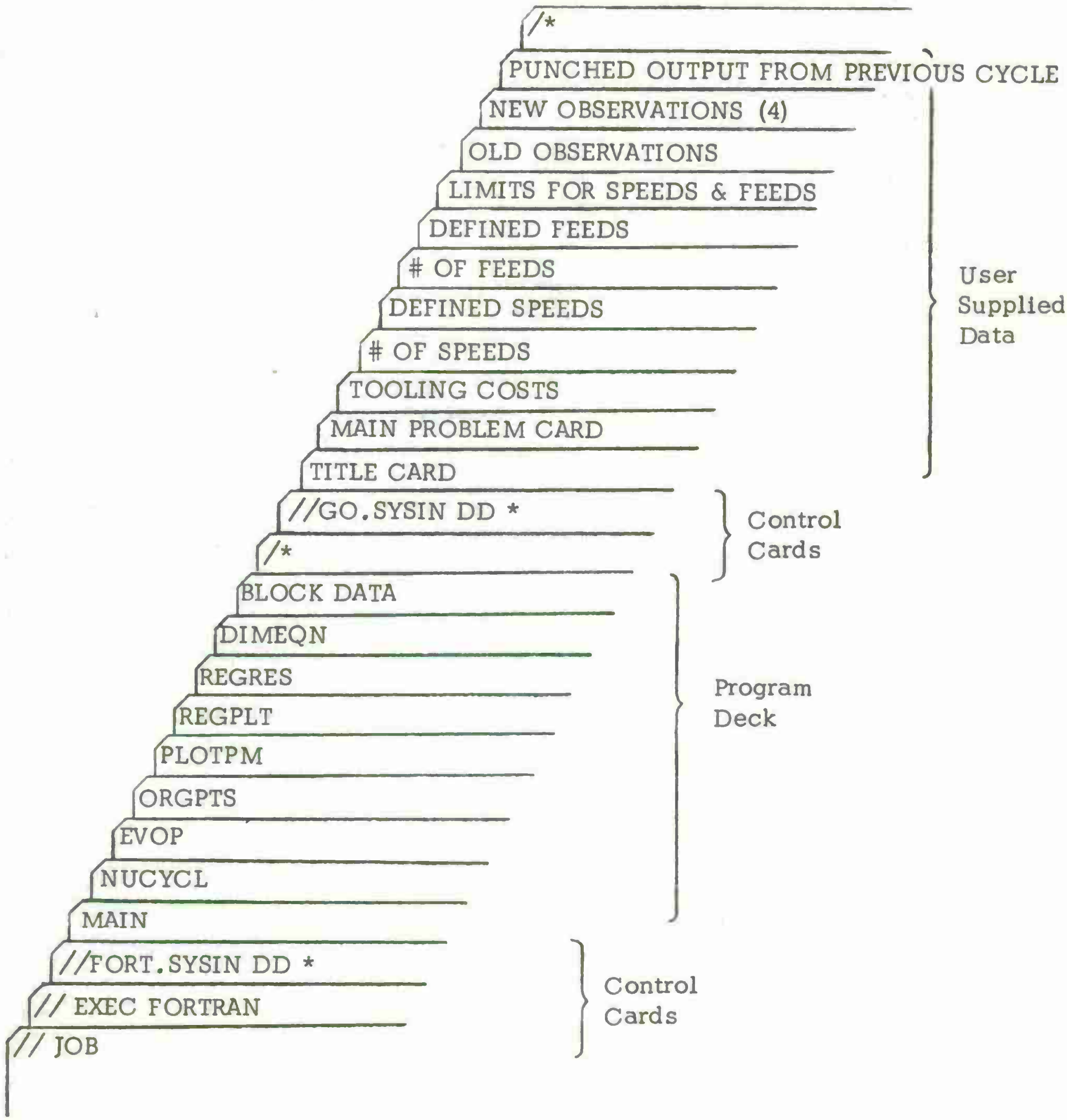
2. The number of feeds defined for this operation must be less than or equal to 50.

3. Observations must be inputted in groups of four.

4. No constraints other than the limits on the speeds and feeds are taken into account by this program.

G.2 Input-Output Descriptions

G.2.1 Program Set-ups



MACHOP Deck Set-up

G.2.2 Input Formats

The input formats for the MACHOP program are given in Figure G.1. These include:

1. Title Card (20A4) (Required)

   The Title Card consists of user supplied identification information punched in columns 1-80.

2. Main Problem Card (5I3, T21, 5F10.4) (Required)

cc	Variable	Description
1-3	IPH	Current Phase Number (Right justified)
4-6	ICYC	Current Cycle Number (Right justified)
7-9	IOP	Operation Type: IOP= (Right justified) 1: single operation 2: multiple operation 3: numerically controlled operation (N/C)
10-12	IMAX	1: If limits for speed and feed are specified (Right justified) 0: Otherwise
13-15	NTLC	Number of different tools (Right justified)
21-30	RLO	Rate for labor and overhead
31-40	AVES(COST)	Preliminary estimate of the standard deviation of the cost observations
41-50	AVES(P/R)	Preliminary estimate of the standard deviation of the production rate observations
51-60	BSP	Base speed for N/C operations (Must be present when IOP=3, cc 7-9)
61-70	BFD	Base feed for N/C operations (Must be present when IOP=3, cc 7-9)

3. Tool Cost Card (Required)

cc	Variable	Description
1-10	TLC(1)	Cost of a tool edge for tool no. 1
11-20	TLC(2)	Cost of a tool edge for tool no. 2
21-30	TLC(3)	...

Note: there must be exactly NTLC (cc. 13-15, M.P.C.) tool edge costs reported.

4. Speed Environment (I3/8F10.4) (Required)

Card 1: cc 1-3, NSPD, Number of speeds defined in the speed environment (NSPD ≦ 100; Right justified)

*Cards 2, 3,...: Defined speeds (rpm) for the environment in ascending order. (There must be exactly NSPD speeds inputted.)

5. Feed Environment (I3/8F10.4) (Required)

Card 1: cc 1-3, NFD, Number of feeds defined in the feed environment (NFD ≦ 50; Right justified)

*Cards 2, 3,...: Defined feeds (ipr) for the environment in ascending order. (There must be exactly NFD feeds inputted.)

6. Feed-Speed Limits (4F10.4) (Optional)
This card must be present if IMAX = 1, cc. 10-12 M.P.C.

cc	Variable	Description
1-10	SMAX	Maximum speed allowed for this operation
11-20	SMIN	Minimum speed allowed for this operation
21-30	FMAX	Maximum feed allowed for this operation
31-40	FMIN	Minimum feed allowed for this operation

---

*For N/C operations the speeds and feeds are the percentage overrides to be considered in this analysis (not fractional equivalents).

7. Observation Cards (8F10.4) (Required)

cc	Variable	Description
1-10	X(1,i)	Observed speed setting (rpm)
11-20	X(2,i)	Observed feed setting (ipr)
21-30	X(3,i)	Number of parts produced
31-40	X(4,i)	Time (in minutes) expended on this operation
41-50	X(5,i)	Number of tool edges for tool #1
51-60	X(6,i)	Number of tool edges for tool #2
61-70	X(7,i)	...

NOTE: Tool edges must be reported for exactly NTLC (cc. 13-15, M.P.C.) tools for each observation.

G.2.3 Input Requirements

1. General input requirements for the use of the MACHOP routine are:

   a. All variables indicated to be right justified are integer values and must not have decimal points punched.

   b. All other values are real numbers and should have their decimal points punched.

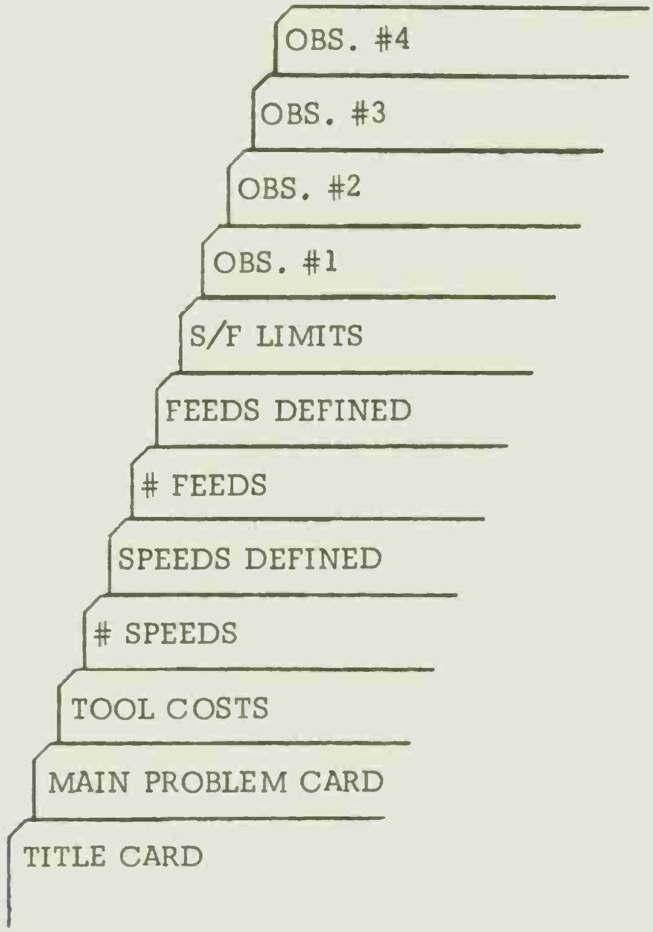
   c. Observations must be read in groups of four.

   d. Phase and cycle numbers must be accurate. (Phase indicates which set of four points is being observed and cycle indicates the number of observations which have been taken at each point.)

   e. Punched output from one cycle must be included in the input of the next cycle.

2. Specific input requirements for the MACHOP routine differ for each category of input. For clarity, sample deck set-ups are defined for each major situation.

a. Case I: Initial phase and cycle with an estimate of the standard deviation.



1. Title Card (Required)

2. Main Problem Card (Required)

IPH = 1	(cc 1-3)
ICYC = 1	(cc 4-6)
IOP = 1,2,3	(cc 7-9)
IMAX	(optional)
NTLC	(cc 13-15)
RLO = Value	(cc 21-30)

AVES (COST) = Standard Deviation Estimate (cc 31-40)
AVES (P/R) = Standard Deviation Estimate (cc 41-50)

3. Tool Costs (Required)

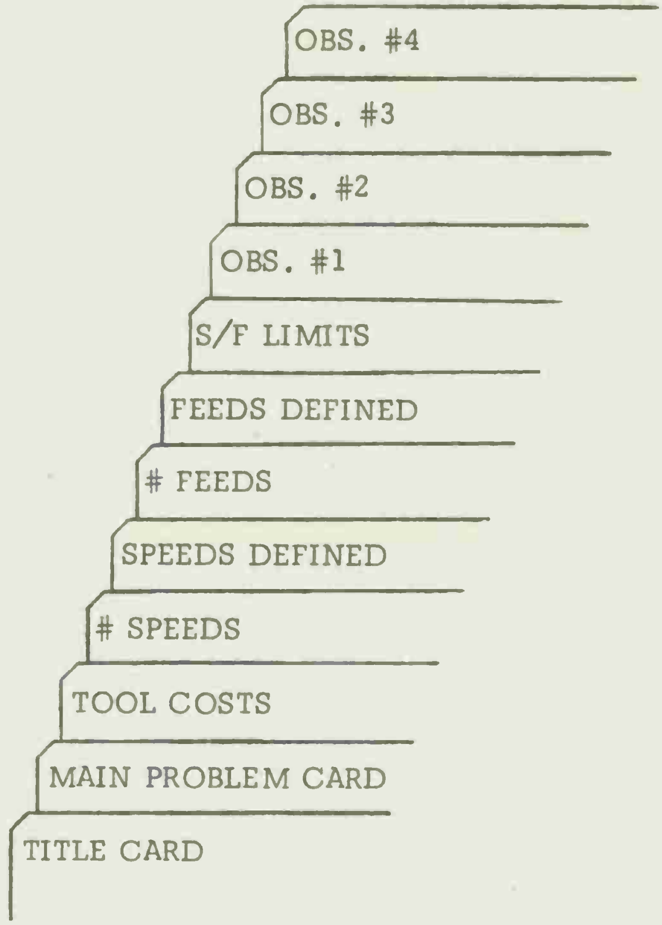
4. Speed Definitions (Required)

5. Feed Definitions (Required)

6. Speed and Feed Limits (Optional)

7. Observations (Exactly four (4) required)

b. Case II: Initial phase and cycle without an estimate of the standard deviation.*



1. Title Card (Required)

2. Main Problem Card (Required)

IPH = 1	(cc 1-3)
ICYC = 1	(cc 4-6)
IOP = 1,2,3	(cc 7-9)
IMAX	(optional)
NTLC	(cc 13-15)
RLO = value	(cc 21-30)

3. Tool Costs (Required)

4. Speed Definitions (Required)

5. Feed Definitions (Required)

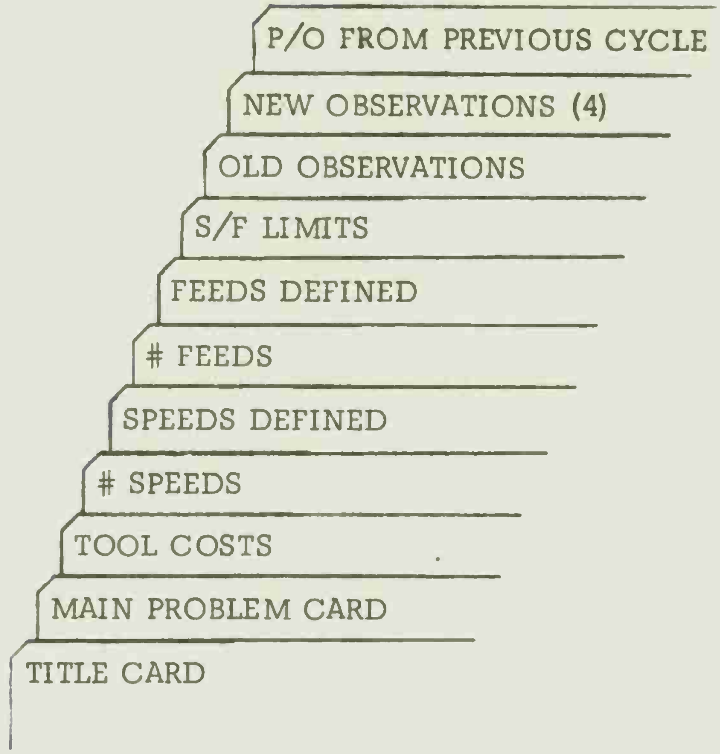
6. Speed and Feed Limits (Optional)

7. Observations (Exactly four (4) required)

---

*A limited output will result since no estimates of the standard deviation are available.

c. Case III: Non-initial cycle.



1. Title Card (Required)

2. Main Problem Card (Required)

IPH = Phase Number	(cc 1-3)
ICYC = Cycle Number	(cc 4-6)
(NOTE: IPH = 1 and ICYC = 1 not used)	
IOP = 1,2,3	(cc 7-9)
IMAX	(optional)
NTLC	(cc 13-15)
RLO = value	(cc 21-30)

3. Tool Costs (Required)

4. Speed Definitions (Required)

5. Feed Definitions (Required)

6. Speed and Feed Limits (Optional)

7. Old Observations (Required)

8. New Observations (Exactly four (4) required)

9. Punched Output from Previous Cycle (Required)*

---

*Note: After each cycle, the old punched output is discarded and is replaced by the new observations and new punched output.

Card											
Title Card	Identification of the Study										
Main Prob Card	IPH	ICYC	IOP	IMAX	NTLC	Not Used	RLO	AVES (cost)	AVES (P/R)	BSP	BFD	Not Used
Tool Cost Card	Tool Change Cost #1	Tool Change Cost #2	Tool Change Cost #3	Tool Change Cost #4	Tool Change Cost #5	Tool Change Cost #6	Tool Change Cost #7	Tool Change Cost #8				
Speed	NSPD	Not Used										
Envi- ron- ment	Speed #1	Speed #2	Speed #3	Speed #4	Speed #5	Speed #6	Speed #7	Speed #8				
Feed	NFD	Not Used										
Envi- ron- ment	Feed #1	Feed #2	Feed #3	Feed #4	Feed #5	Feed #6	Feed #7	Feed #8				
Speed & Feed Limits	MAX Speed	MIN Speed	MAX Feed	MIN Feed	Not Used							
Obser- vations	Speed	Feed	# Parts	Time	# Tools 1	# Tools 2	# Tools 3	# Tools 4				

Figure G.1 MACHOP Input Formats

G.2.4 Output Description

Output from the MACHOP program generally consists of less than 2000 printed lines and five punched cards. The output is as follows:

a. Input information such as feed-speed limits, labor and overhead rates, tool costs, and prior estimates of standard deviations of the response variables (if any).

b. The specified feed-speed environment represented "graphically."

c. The cumulative input data and the computed responses (cost per piece and production rate).

d. A table of the computed responses for this phase and cycle.

e. Evolutionary operation calculations for both the cost per piece and production rate responses.

f. A recommended set of operating conditions for the next experiment (which may be identical to the current set), based on the cost per piece analysis.

g. A graphical representation of the operating conditions recommended in f.

h. The recommended set of operating conditions for the next experiment (which may be identical to the current set), based on the production rate analysis.

i. A graphical representation of the operating conditions recommended in h.

j. The results of the regression analysis and the accompanying analysis of variance table for the cost per piece analysis.

k. The results of the regression analysis and the accompanying analysis of variance table for the production rate analysis.

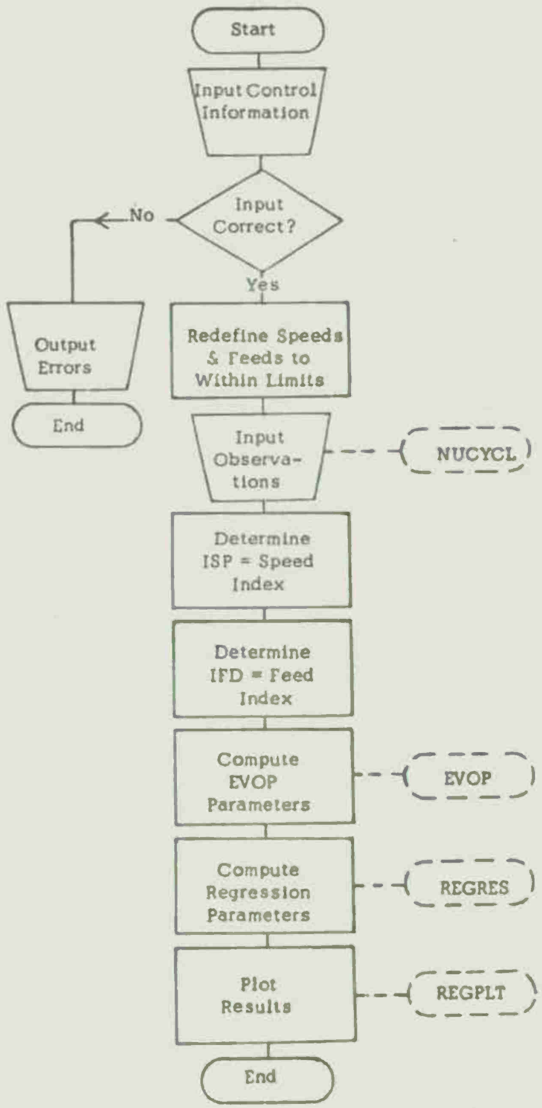
ℓ. The predicted response surfaces for cost/piece and production rate calculated from the respective prediction equations.

Optional output includes a listing of observations, the predicted values, the residuals, the matrices $X'X$ and $(X'X)^{-1}$, and the vector $X'\underline{y}$.

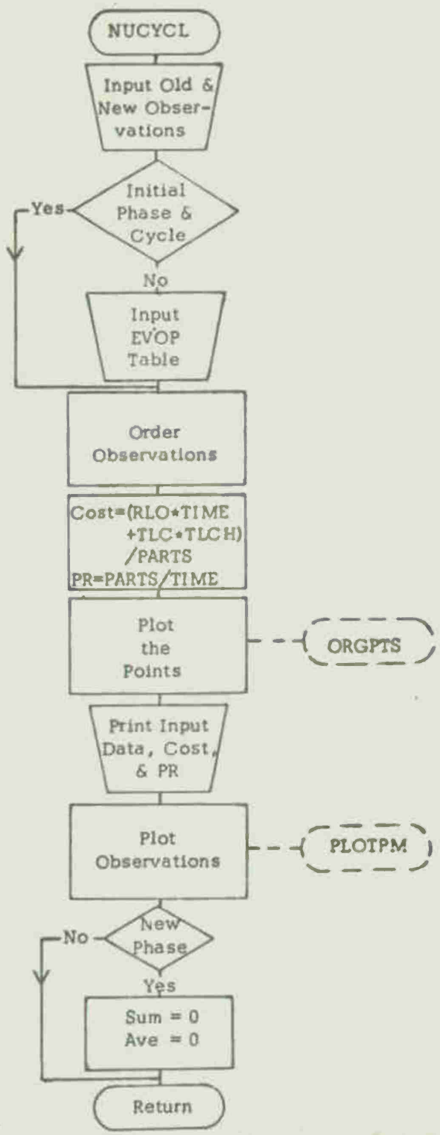
G.3 Systems Material

G.3.1 Flow Chart

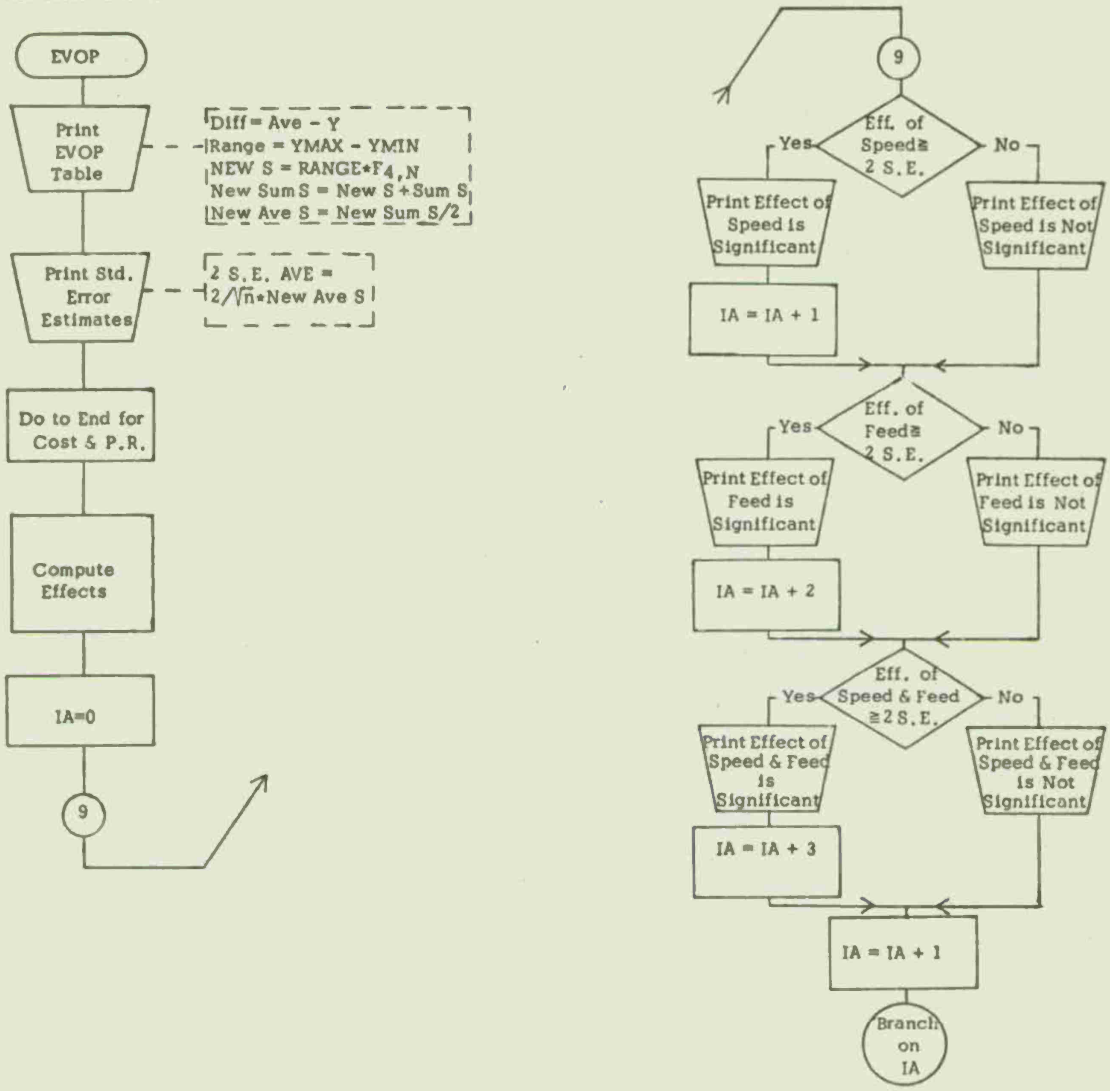
MAIN PROGRAM

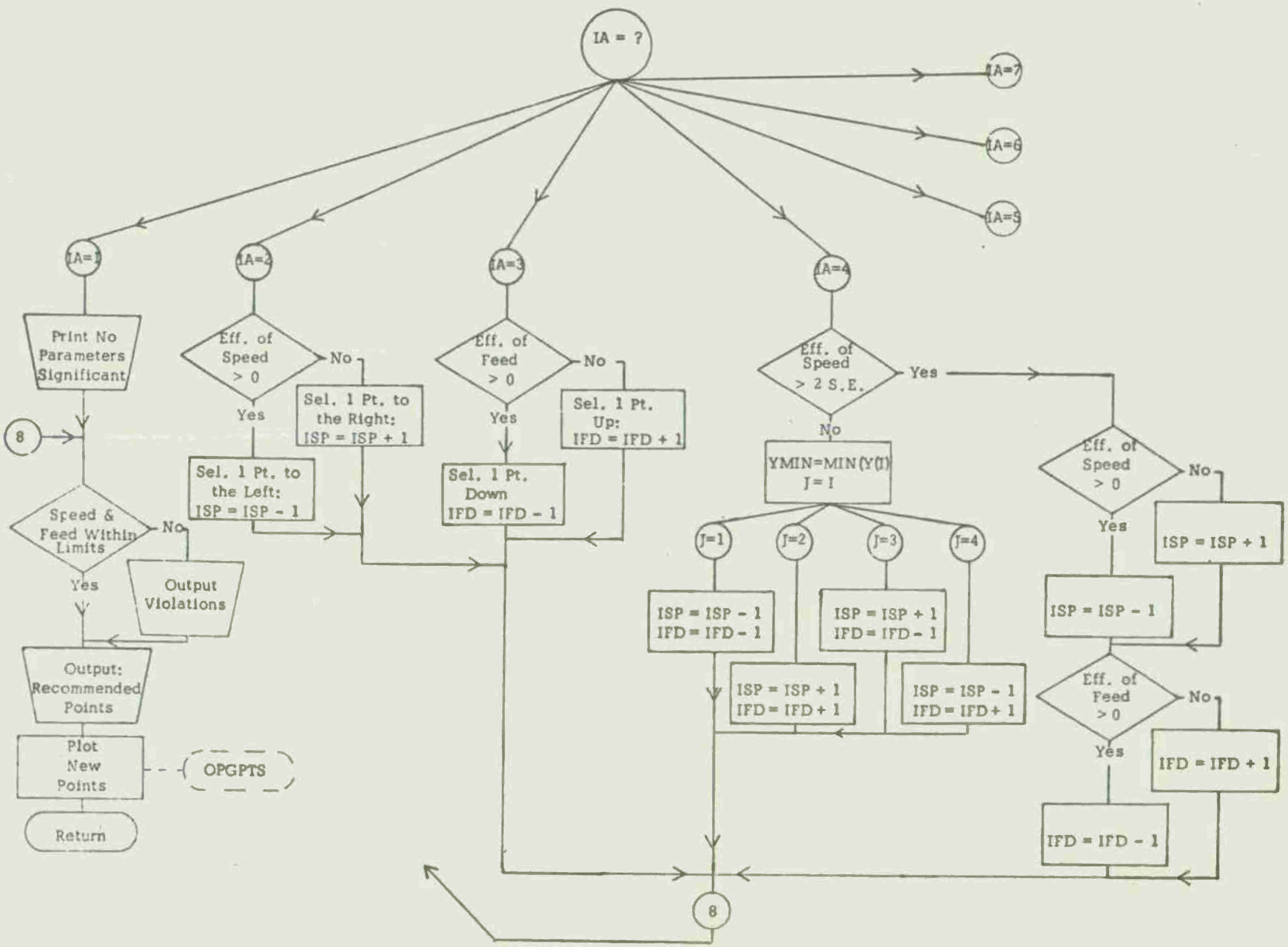


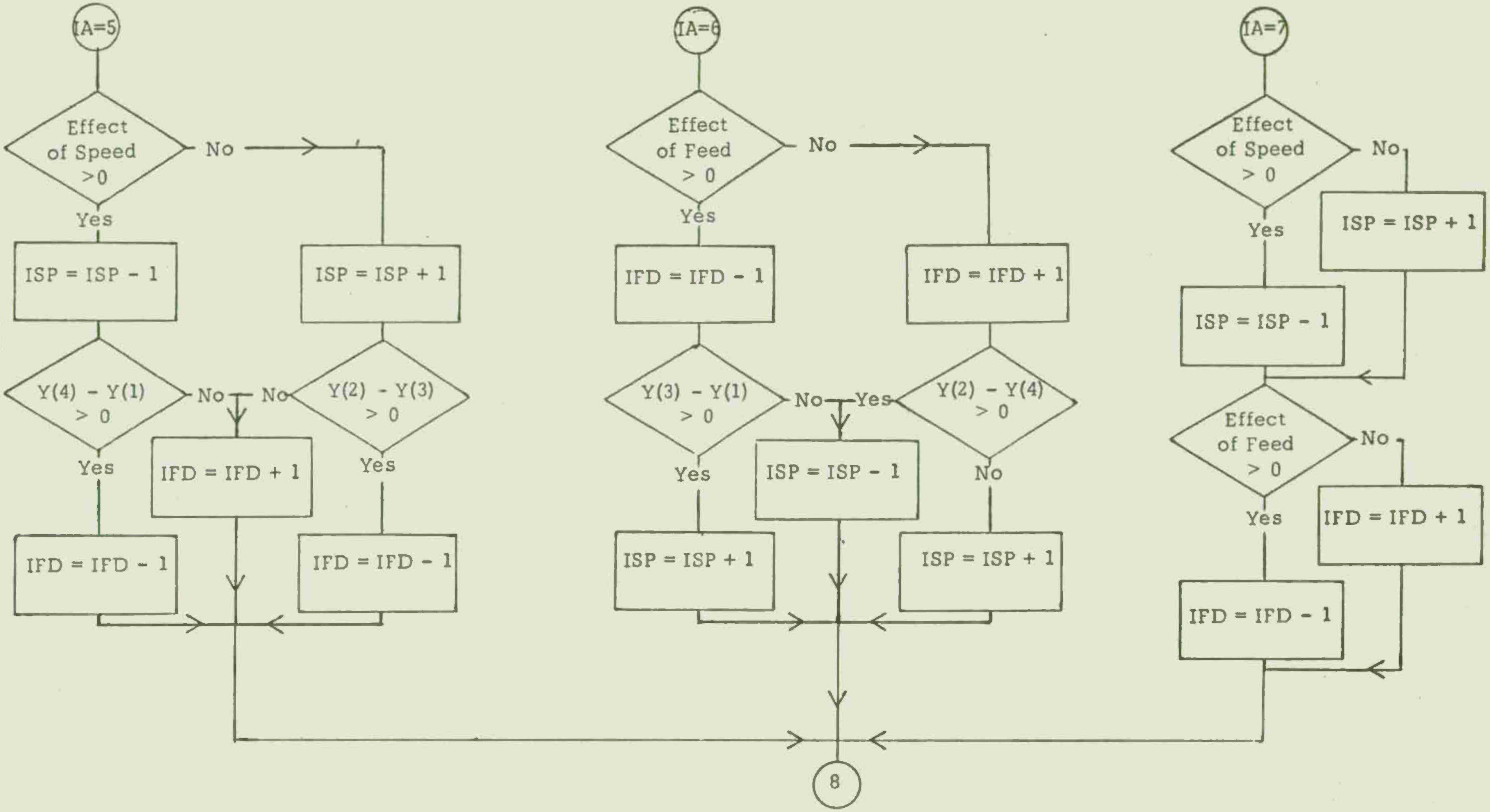
SUBROUTINE NUCYCL



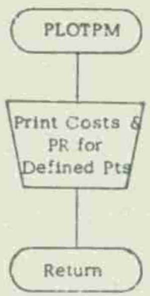
SUBROUTINE EVOP



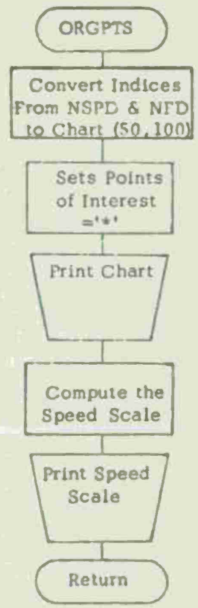

IA = ?
IA=1
IA=2
IA=3
IA=4
IA=5
IA=6
IA=7
Print No Parameters Significant
8
Speed & Feed Within Limits
No
Yes
Output Violations
Output: Recommended Points
Plot New Points
OPGPTS
Return
Eff. of Speed > 0
No
Yes
Sel. 1 Pt. to the Right: ISP = ISP + 1
Sel. 1 Pt. to the Left: ISP = ISP - 1
Eff. of Feed > 0
No
Yes
Sel. 1 Pt. Up: IFD = IFD + 1
Sel. 1 Pt. Down IFD = IFD - 1
Eff. of Speed > 2 S.E.
Yes
No
YMIN=MIN(Y(I)) J = I
J=1
J=2
J=3
J=4
ISP = ISP - 1 IFD = IFD - 1
ISP = ISP + 1 IFD = IFD + 1
ISP = ISP + 1 IFD = IFD - 1
ISP = ISP - 1 IFD = IFD + 1
Eff. of Speed > 0
No
Yes
ISP = ISP + 1
ISP = ISP - 1
Eff. of Feed > 0
No
Yes
IFD = IFD + 1
IFD = IFD - 1
8


IA=5
Effect of Speed >0
No
Yes
ISP = ISP - 1
ISP = ISP + 1
Y(4) - Y(1) > 0
No
No
Y(2) - Y(3) > 0
Yes
IFD = IFD + 1
Yes
IFD = IFD - 1
IFD = IFD - 1
IA=6
Effect of Feed > 0
No
Yes
IFD = IFD - 1
IFD = IFD + 1
Y(3) - Y(1) > 0
No
Yes
Y(2) - Y(4) > 0
Yes
ISP = ISP - 1
No
ISP = ISP + 1
ISP = ISP + 1
IA=7
Effect of Speed > 0
No
Yes
ISP = ISP + 1
ISP = ISP - 1
Effect of Feed > 0
No
Yes
IFD = IFD + 1
IFD = IFD - 1
8

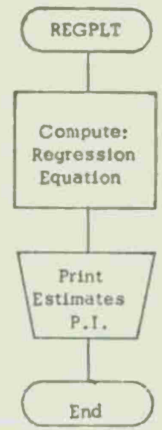
SUBROUTINE PLOTPM



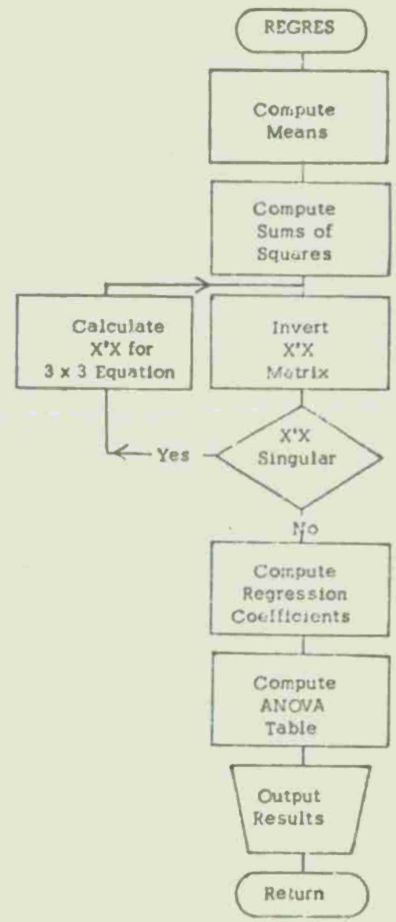
SUBROUTINE ORGPTS



SUBROUTINE REGPLT



SUBROUTINE REGRES



G.3.2 Glossary of Important Variables

Variable Name	Description
ANS	Vector of regression results returned from REGRES subroutine
AVE	Vector of the averages in the EVOP routine
AVES	Estimate of the standard error in the EVOP table
B	Vector of estimates of the b-coefficients in the regression equation
CHART	100 x 50 matrix containing the plot output in the ORGPTS routine
DIFF	Vector of the differences between the average cost at a given point and the newly observed cost
FEED	Vector containing all defined feed settings in ascending sequence
F4N	Vector of the values of $f_{4,n}$ as defined in Box and Draper [3]
ICYC	Cycle number
IFD	Index containing the current feed setting
IPH	Phase number
ISP	Index containing the current speed setting
NFD	Number of feed settings defined in the environment of this operation
NOBS	Number of observations in the current cycle
NSPD	Number of speed settings defined in the environment of this operation
RLO	Labor and overhead rate as reported on the main problem card

Variable Name	Description
SPEED	Vector of all defined speed settings in ascending sequence
SUM	Vector of the sums of the observations
SUMS	Sum of the estimates of the standard error of the observations
TLC	Tool edge cost
TLCH	Observed number of tool edges used
X	Matrix (5xn) of the input observations, both old and new. For observation n, X(1,n) = speed (rpm), X(2,n) = feed (ipr), X(3,n) = number of parts produced, X(4,n) = production time in minutes, and X(5,n) = number of tool edges used.
Y	Matrix (2xn) of the performance indices, both old and new. For observation n, Y(1,n) = cost (dollars/piece), and Y(2,n) = production rate (pieces/minute).

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Report R-CR-74-031, June 74, 146 p. incl. illus. tables, (Contract DAAF03-73-C-0110, AMS Code 3297.16.6779) Unclassified report.

A system for determining optimal machining conditions based on actual production machining data is developed. This system is applicable to analysis and control of single-operation as well as multiple-operations (numerically-controlled) machining. The system incorporates a computer program which provides an evolutionary operation analysis and response surface, regression analysis of two responses, cost per piece and production rate.

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